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STUDY OF FORGEABILITY BASED ON LOCAL STRAIN AND
GRAIN STRUCTURE EFFECTS UNDER VARIED DEFORMATION
RATE AND TEMPERATURE

FINAL REPORT

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STUDY OF FORGEABILITY BASED ON LOCAL STRAIN AND
GRAIN STRUCTURE EFFECTS UNDER VARIED DEFORMATION RATE AND TEMPERATURE

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EXECUTIVE SUMMARY

An attempt was made to develop a deformation model from the data of local strain measurements.

Nodular cast iron is taken as a modelling material because its microstructure contains good spherical nodules, which are suitable for the study of deformation, forgeability, etc. Cracking will occur under certain deformation conditions and the deformation can be recorded by following the changes in nodule shape and orientation. Also, different forgeabilities can be obtained by changing the structure and composition of the matrix.

Local strains in any area of interest can be determined by measuring the shape change of nodules in terms of an aspect ratio b/a (a = major axis, b = minor axis of deformed nodules) from sectioned specimens after deformation.

The results show a good agreement with the macroscopic deformation measured from gauge length changes. Cracks can also be studied in this way: i.e. basic information such as crack initiation, propagation and local strain at or near crack tips can be obtained.

Etude du forgeabilité basé sur les tensions localisées
et les effects de la structure granulaire sous différents taux de
déformations et températures

DSS Contrat # 20ST 23440-4-9327

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Sommaire Exécutif

Un essai a été fait pour développer un modile à parter de mesures de tensions localisées.

L'acier coullé nodulaire est utilisé comme material pour le modile à cause de sa microstructure qui contient des nodules sphéuques, lesquels sont adéquats pour l'étude de déformation et de formabilité, etc. Des fissures seront produites sous certaines conditions de déformation et cette déformaton jeut être enregistrée par l'observation du changement de forme et d'orientation des nodules. Aussi, différentes formabilites jeuvent être obtenues en changeant la structure et la composition de la matrice. Des tensions localisées dans n'emporte quelle région d'intérêt jeuvent être déterminées en mesurant le changement de forme des nodules eu termes d'allongement de b/a (a = axe majeur, b = axe mineur des nodules déformés) d'échantillons sectionnés après déformation.

Les résultats concordent avec les mesures de déformation macroscopique prisent à partir de changements de galarits de longueur. Les fissures peuvent aussi être étudiées de cette façon i.e. des informations de bases telles que l'initiation des fissures, leurs propagations et la tension localesée à ou jues de la fissures jeuvent être obtenues.

1. INTRODUCTION

As new, more difficult-to-work materials have recently developed, the forgeability of these materials has become increasingly important. Since the "trial and error method" is time consuming and inadequate, many researchers have tried to establish criteria by which the forging limit can be predicted.

Forgeability is defined as the tolerance of a metal or alloy for deformation without failure. Usually the limit for upset forging without failure by radial or peripheral cracking is considered a measure of forgeability. Kuhn developed a forming limit for bulk deformation [1] based on this definition. However, this is a rough evaluation because inner cracks during deformation cannot be predicted. Also ductile fracture is an extremely complex phenomenon that is dependent on the microstructure of the materials, the complex stress and strain states, and the temperatures developed during the deformation operation. Another definition has been given by Cockroft and Latham [2], who suggest that workability is a function of both material and process variables, as expressed by

$$\text{workability} = f_1 \times f_2,$$

where f_1 is a measure of the true ductility of the material (largely dependent on the microstructure of the material) and f_2 is a factor indicating the effect of process variables such as geometry, friction, temperature, strain rate, etc. on material behaviour.

In order to establish a criterion generally applicable for forging processes, this study attempts to correlate forgeability with local strain measurements and grain structure changes under varied deformation rates and temperatures. Generally, local strain on a free surface can be measured by strain gauges or the ruled grid method. However, it is not easy to measure local strain at or near crack tips within the body. To date, no one has developed a suitable method to measure the local strain within a body for the study of forgeability. In this study, nodular cast irons with different matrixes have been chosen as ideal materials to conduct forgeability tests because the shape of the undeformed graphite particles can be made closely spherical. Hence these particles may be used to provide suitable markers for local strain measurement: the shape change of a nodule after deformation gives a measure of local strain. This method can be mathematically proven and the experimental work shows a good agreement between macro- and micro-strains. The assumption implicit here is that the strain field is homogeneous over the region occupied by the graphite nodule, in order that quantitative data may be obtained. However, in those regions where the strain may vary sharply with distance (as, for instance, near a crack tip), observation of the shape change of the graphite nodules can give semi-quantitative data of considerable importance in improving our knowledge of deformation processes.

2. MATERIALS PREPARATION

2.1 Materials Selection

According to the definition, forgeability is always concerned with deformation and fracture. Therefore, the ideal material for developing

forgeability criteria should have mechanical properties which can stand some degree of deformation before cracking under varied test conditions such as different temperatures and strain rates. Also, if the grain size were uniform, then after deformation the local strain could be measured by grain shape change. However, the grain size and boundary shape may change as the test conditions change. For example, the grain size and boundary shape of a material will change as the temperature increases, and grains will be broken down into smaller grains by large strain deformation. Therefore the effects of temperature and deformation should be considered if local strain is to be determined by measuring grain size change. Moreover, the apparent grain size in a sectioned specimen is generally not uniform, not only because of the difficulty of control but also due to the different projection of grains on the plane of the section.

In this study, valve steels, 304 stainless steel and nodular cast iron have been used to conduct forgeability tests at room temperature. The compositions of these materials are listed below:

Nodular cast irons were adopted for this forgeability study for the following reasons:

- a) They have suitable mechanical properties for a test of forgeability compared to valve steels, 304 stainless steel and pure iron. Valve steels are not very ductile, and only small deformations can be obtained before crack initiation. 304 stainless steel and pure iron are too ductile and so it is difficult to obtain a crack. However, with nodular cast irons a reduction of 35 - 60% can be obtained before cracking.
- b) It is relatively easy to obtain local strain data because of the specific structure of nodular cast iron. That is, the nodules

- themselves provide ideal markers for local strain measurements.
- c) Structures of nodular cast irons are relatively uniform if the specimens are cast in small sizes, and the "as cast" structure is free of any deformation. Nodules are also relatively stable at moderate temperature and deformation.
 - d) They are relatively easy to produce and machine to size.
 - e) The iron matrix may be given a wide variety of structures and properties.
 - f) The forgeability of cast iron has recently become an item of considerable interest to both research and industry [3,4].

2.2 Materials Preparation

Once nodular cast irons were chosen as the test materials, the control of nodularity (nodule shape, size and distribution) became a key point. Because the local strain was measured by the shape change of nodules, the sphericity of the original nodules had a critical affect on the accuracy and precision of local strain values.

It was necessary to develop casting techniques to get sound castings with spherical nodules which were evenly distributed as well as of controlled size range. Subsequently, different matrixes of nodular cast irons were produced by heat-treatment and alloying.

In this study, an investment casting technique was developed to control the nodularity of nodular cast iron. Two types of nodular cast irons were produced by this technique: those with ferritic, pearlitic and ferritic/pearlitic (F-P) and those with austenitic (A) matrixes. F-P nodular cast iron was made with different nodule sizes and distributions by

employing different cooling rates.

2.2.1 Materials

High purity pig iron, Fe-Si and steel (alloys # 1,2,3 in Tables 2 and 3) were used as main charge materials for making F-P nodular cast irons. For the ferritic, pearlitic and ferritic/pearlitic nodular cast irons the same composition was used but different heat treatments were applied to get different matrices after casting.

0.7% of Ni-15% Mg was added as nodularizer, followed by a small addition (0.02%) of mish-metal (cerium) and 0.4% of Superseed (Si 49.27%, Al 0.23%, Ca 0.07%, Sr 0.07% Fe 50.36%) as an inoculant. The composition of the ferritic/pearlitic nodular cast iron and master alloys are shown in Table 2.

For making austenitic nodular cast iron, 20 wt.% Ni was added with the same treatment but without the cerium addition. The composition of the master alloy and of the cast irons are given in Table 3.

2.2.2 Molding, Melting and Casting

Molding

Keel-block sand and investment ceramic molds were used for making F-P nodular and austenitic nodular cast irons. The patterns of the molds and their dimensions are shown in Figures 1-4. Standard investment casting procedures were employed for making ceramic molds. Wax patterns were made and coated with a ceramic slurry, then the wax was removed by "flash" dewaxing.

Melting and Nodularising Treatment

Melting was done in two Tocco induction furnaces. The raw materials were charged into the large furnace (19 cm diameter x 28 cm depth) for rapid melting. The melt was then transferred to the smaller ladle (9cm diameter x 19 cm in depth) for melt treatment. The temperature was measured with a Pt - Pt-13%Rh thermocouple. All melts were superheated to a temperature of about 1500°C, at which point the slag was removed by skimming the melt before pouring into a ladle.

The nodularizing treatment consisted of placing 0.7% of Ni-15% Mg on the bottom of the preheated ladle and pouring the 1500°C liquid metal over it as quickly as possible. During pouring, the stream of liquid metal was directed away from the location of the Ni-Mg alloy to prevent it from floating to the surface and oxidising. After pouring liquid metal into the ladle, further additions of 0.02% cerium and 0.4% "Superseed" were stirred in with a graphite bar. Then the liquid was quickly poured into molds at about 1450°C.

Casting

After the nodularizing treatment, the liquid metal was poured into a keel-block sand mold or ceramic mold which had been preheated at about 800°C for 24 hours and furnace-cooled to room temperature over twenty hours to remove moisture. After pouring, the sprues were covered with refractory insulating fiber to reduce heat loss.

2.2.3 Heat Treatment

The F-P nodular cast irons can be obtained from the same composition by different heat treatments. Because of poor nodularity, the keel-block castings were rejected. The casting specimens from investment ceramic molds were put into a container packed with saw chips of nodular cast iron. In addition, an argon atmosphere was used to make sure there was no oxidization/decarburization. The heat treatment was done in a Lindberg heavy-duty furnace. The heat treatment for different matrices was as follows:

The ferritic nodular iron specimens were heated at 900°C for four hours, furnace-cooled to 720°C (with the furnace power turned off), then forced to cool at a controlled rate of 5°C/hour for five hours. Finally the power was turned off again and the specimens allowed to cool in the furnace to room temperature.

The pearlitic nodular iron specimens were heated at 900°C for five hours then cooled in forced air. The ferritic/pearlitic nodular iron was obtained in as-cast condition, and was cooled in air after pouring the liquid metal into the ceramic mold.

In order to obtain the austenitic nodular cast iron, Ni was added to the melt. This structure was not sensitive to the heat treatment.

2.2.4 Control of Nodular Shape, Size and Distribution

As described in section 2.2 the control of nodularity (nodule shape, size and distribution) is critical if the shape change of nodules is to be used as an indicator of the local strain. Due to this requirement, a

suitable casting technique had to be developed. This has been described in Sections 2.2.1, 2.2.2 and 2.2.3. Our casting technique gave closely spheroidal nodules with a given size range and distribution. However the nodularity is sensitive to the melt-treatment and cooling rate. In preliminary experiments various cooling rates were obtained with different section sizes of ceramic mold. Differences in nodule shape, size and distribution among the specimens from smallest section to largest section were very evident. In a given cross-sectional area, many nodules of smaller size were found in the smaller specimens and fewer nodules of larger size were found in the larger specimens. The microstructures are shown in Figures 5 and 6. Specimens number 1 and 2 (in order from small to large size) were chosen as casting cross sections because their microstructures showed the best nodularities among the five different cross sections of castings (Fig. 5).

The keel-block method was discontinued because its microstructure showed poor nodularity due to slow cooling rate.

2.2.5 Structure and Soundness Checking of Castings

a) Soundness

No micro-shrinkage could be seen by microscopic examination of the cuts for any casting sections, as shown in Figure 7.

b) Metallography Examination

A mixture of nitric, acetic and hydrochloric acid, and glycerol in

proportion of 10:10:15:5 was used as the etchant for austenitic nodular cast iron. 2% nital was used for etching F-P nodular cast irons. Unetched and etched microstructures of different matrixes of nodular cast iron are shown in Figures 8 - 11.

3. THEORETICAL APPROACH

In this study local strains are determined by measuring the aspect ratio b/a of the graphite nodules after deformation. "a" is the major axis and "b" is the minor axis of the ellipse after sectioning of the deformed specimen along the axis of compression. It can be mathematically proven that the shape of the nodules changes from spherical to oblately elliptical during the deformation, and that the aspect ratio remains constant whenever the sectioning is parallel to the main axis of the specimen. Also the aspect ratio of a nodule can be expressed as a mathematical function of the macroscopic reduction of the specimen.

3.1 Shape of Nodules after Deformation

Assuming that the graphite nodules are isotropic and that volume is constant during uniform plastic deformation of nodular cast iron then

$$\epsilon_x + \epsilon_y + \epsilon_z = 0 \quad (1)$$

where ϵ_x , ϵ_y and ϵ_z are strains of the deforming body in the x, y and z directions.

Since the stress is applied only along the z-axis, geometric

symmetry allows us to set

$$\epsilon_x = \epsilon_y$$

Thus equation (1) becomes

$$\epsilon_z = -2\epsilon_x = -2\epsilon_y \quad (2)$$

For a sphere

$$x^2 + y^2 + z^2 = R^2 \text{ (constant)} \quad (3)$$

If the sphere is deformed, with (x,y,z) transforming to (x',y',z') by:

$$x' = x (1 + \epsilon_x)$$

$$y' = y (1 + \epsilon_x)$$

$$z' = z (1 + \epsilon_z)$$

Then
$$\frac{x'^2}{(1+\epsilon_x)^2} + \frac{y'^2}{(1+\epsilon_x)^2} + \frac{z'^2}{(1+\epsilon_z)^2} = x^2 + y^2 + z^2 \quad (4)$$

Combining (3) and (4) and simplifying them, we find

$$\frac{x'^2}{a^2} + \frac{y'^2}{b^2} + \frac{z'^2}{c^2} = 1, \quad (5)$$

which is the equation of an oblate ellipsoid, with

$$a = b = R(1 + \epsilon_x)$$

$$c = R(1 + \epsilon_z) = R(1 - 2\epsilon_x)$$

3.2 Independence of Aspect Ratio

After uniform deformation, the shape of nodules changes from spherical to oblately elliptical. If the deformed specimen is sectioned, the cross-sections of the nodules will have elliptical shapes. The aspect ratio of the ellipses is independent of sectioning as long as it is parallel to the main axis of specimen (e.g. the axis of cylinder). It can be proven as below:

If an oblate ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{b^2} = 1$$

is sectioned parallel to z direction, then at $y = y_1$, the ellipsoid becomes

$$\frac{x^2}{a^2} + \frac{y_1^2}{a^2} + \frac{z^2}{b^2} = 1$$

Therefore $\frac{x^2}{a^2} + \frac{z^2}{b^2} = 1 - \frac{y_1^2}{a^2}$

or
$$\frac{\frac{x^2}{a^2}}{1 - \frac{y_1^2}{a^2}} + \frac{\frac{z^2}{b^2}}{1 - \frac{y_1^2}{a^2}} = 1$$

This is an ellipse in the x - z plane whose major and minor axes a^* and b^* are given by:

$$a^* = \sqrt{a^2 \left(1 - \frac{y_1^2}{a^2}\right)} \quad b^* = \sqrt{b^2 \left(1 - \frac{y_1^2}{a^2}\right)}$$

the aspect ratio is then

$$\frac{b^*}{a^*} = \frac{\sqrt{b^2(1 - \frac{y_1^2}{a^2})}}{\sqrt{a^2(1 - \frac{y_1^2}{a^2})}} = \frac{b}{a}$$

If sectioning is at $y = y_2$

$$\frac{b^{**}}{a^{**}} = \frac{\sqrt{b^2(1 - \frac{y_2^2}{a^2})}}{\sqrt{a^2(1 - \frac{y_2^2}{a^2})}} = \frac{b}{a}$$

Thus aspect ratio is independent of sectioning. Because of the geometric symmetry, the same results would be obtained for sections which intercept any point on the x-axis. These ellipses are "similar" ellipses since their aspect ratios are the same.

3.3 Relation Between Aspect Ratio and Reduction

Since most forging operations are compressions the corresponding deformation is expressed in terms of reduction (e) along the axis of compression:

$$e = \frac{h_o - h_f}{h_o} \quad (6)$$

Where h_o and h_f are original and final heights of the deforming piece.

During the deformation, the shape of a nodule changes from spherical to ellipsoidal. Assuming the volume of a nodule remains constant, then:

$$\frac{1}{6} \pi D^3 = \frac{4}{3} \pi \frac{b}{2} \left(\frac{a}{2}\right)^2 \quad (7)$$

where D - diameter of sphere

a - major axis of oblate ellipse

b - minor axis of oblate ellipse

The corresponding reduction of the sphere would be

$$e = \frac{D - b}{D} \quad (8)$$

The aspect ratio c is defined as

$$c = b/a \quad (9)$$

Substituting (9) into (7) gives:

$$\frac{1}{6} \pi D^3 = \frac{4}{3} \pi \frac{ca}{2} \left(\frac{a}{2}\right)^2,$$

$$\text{or } D^3 = ca^3$$

$$\text{Therefore, } D = a \sqrt[3]{c} \quad (10)$$

Substituting (9) and (10) into (8) gives:

$$e = \frac{a \sqrt[3]{c} - ca}{a \sqrt[3]{c}}$$

$$\text{or } e = 1 - c^{2/3} \quad (11)$$

As proven in Section 3.2 the aspect ratio is independent of sectioning; therefore the engineering strain (reduction) is independent of sectioning also.

4. EXPERIMENTAL WORK

Compression, tension and three-point bending tests of nodular cast iron were conducted at room temperature. The deformation was observed and the local strain was measured as the aspect ratio b/a of the nodules from the sectioned specimen after deformation. The results showed a good agreement with the theoretical approach:

- a) The shape of nodules changed from spherical to oblate ellipsoid during compression. This was clear from the fact that nodules appeared circular in the transverse section and elliptical in the longitudinal section (Figures 12 and 13).
- b) The aspect ratio was independent of sectioning. Wherever the sectionings were parallel to the main axis of the deformed cylinder, the measured aspect ratios were almost the same.
- c) The micro strain (local strain) had a good agreement with macro strain (engineering strain).

Since the deformation zones (deformation distribution) could be clearly distinguished by the appearance of deformed nodules in the longitudinally sectioned specimens, local strains in these zones were measured.

The fractures were studied and local strains at or near these cracks were measured. The experimental procedure will be described and the results will be shown in detail in this section.

4.1 Specimen Preparation

Several specimens of F-P nodular cast irons and austenitic nodular cast iron were machined into cylinders of 15 mm diameter x 27 mm length. Some specimens were machined into different lengths for the tests of free-surface strain measurements.

Specimens for tensile and three-point bending tests were machined to the desired dimension from ferritic nodular iron. The surfaces were then polished. Finally grids of 2mm x 2mm were inscribed on one of the polished surfaces of both tensile and bending specimens using a micro-hardness indenter. It was important that the surface finish be good in order to observe the initiation and propagation of cracks. In addition, accurate dimensions were required in order to compare the results with each other.

4.2 Compression Test

The compression tests were conducted at room temperature using the 200,000 lb hydraulic machine at PMRL, CANMET. The fractures during compression were determined by the load change in the time-load chart recording. The deformation of nodules was observed, and a general evaluation of forgeability of nodular cast irons was made. Fractures were studied and the local strains and free-surface strains were measured.

4.2.1 Deformation of Nodules

Among the nodular cast iron investment castings, an austenitic

nodular cast iron containing mostly rounded nodules in its microstructure (Figure 14) was chosen and specimens were machined from it for the observation and measurement of deformation of nodules. After deformation the shape of nodule cross sections changed from circular to elliptical in the longitudinal section and remained circular in the transverse section. Typical specimens are shown in Figure 15, demonstrating the dimensions before and after frictionless compression [5]. The specimen in Figure 15 was deformed 24% without barrelling. After it was sectioned longitudinally, the specimen showed uniform deformation without different deformation zones; therefore this frictionless compression could be used for comparing micro- and macro-deformation. Macro-deformation was calculated in reduction (24% for this specimen) and micro deformation was measured by the aspect ratio b/a in different sections which were cut in the longitudinal direction. The results showed that the average aspect ratios were 0.64, 0.63, and 0.64 in three different sections. Since the values were almost the same in the three sections, the experimental evidence confirms that the aspect ratio b/a is independent of sectioning. According to the relation derived in section 3.3, the local deformation in terms of reduction could be calculated from equation (11) as:

$$e = 1 - c^{2/3} = 1 - 0.64^{2/3} = 0.26$$

It showed a good agreement with macro deformation for a reduction of 24%.

4.2.2 General Evaluation of Forgeability of Nodular Cast Irons

Nodular cast irons with different matrixes have different mechanical properties. Since they were chosen as test materials and are also of

industrial interest, it was necessary to evaluate the forgeability of these materials. Cold forgeability was evaluated by a compression test (without lubrication) on the 200,000 lb hydraulic machine at PMRL, CANMET. Since there is no equipment sensitive enough to stop the hydraulic machine at crack initiation, the fracture during compression was determined by the load change in a time-load recording, then adjusted by slightly decreasing and increasing the reduction of identical specimens in the vicinity of the preliminary value. The results are shown in Table 4.

Free-surface deformation and cracks were observed by Scanning Electron Microscopy (SEM). Figures 16 and 17 show the deformed surface of a ferritic nodular cast iron after compression testing. The graphite nodules were squeezed-out from the surface or subsurface (Figures 16-18). Surface deformation of austenitic nodular cast iron was also observed by SEM, but no obvious sign of squeezing out of nodules was evident (Figure 19).

The results show that the deformation properties of a nodular cast iron depend mainly on the type of matrix. The nodules behave as incompressible cheese-like regions in the matrix and deform easily.

Surface cracks in the nodular cast iron started at the equator of the cylindrical specimens and propagated along grain boundaries at about 45° with the deformation axis by the linking up of nodules (Figure 20).

4.2.3 Deformation Zones

After compression testing, the deformation of the nodular cast iron could clearly be seen from nodule-shape changes as viewed on polished longitudinal sections. A number of distinct zones of deformation, such as

dead zones, shear bands, etc. can easily be identified (Figure 21). Since the aspect ratio method has been theoretically and experimentally proven, local strains can be measured by this method.

An austenitic nodular cast iron specimen (its structure is shown in Figure 14) was examined after a crack appeared during a compression test with 38% reduction. Deformation zones can be clearly identified at about 200x magnification by observing the nodule shape and orientation in the matrix using the longitudinally sectioned specimen which is shown in Figure 21. The local strains were computed from the aspect ratio b/a of the deformed nodules. Micrographs were taken from the typical area of interest in different deformation zones for the measurement of local strain. The results of local strain measurements are given in Table 5.

The width of the shear band in this specimen was measured by measuring the width of the area which had marked changes of aspect ratios and rotation of the nodules. The shear band width was found to be about 0.25 mm. These areas are shown in Figures 22-25.

4.2.4 Local Strain at or Near Crack Tips

Since the aim of this study is to establish a criterion generally applicable for forging processes, and to correlate forgeability with local strain measurements and grain structure changes under varied deformation conditions, the use of local strain measurement to study cracks is essential.

After the compression test, two cracks were found in the sectioned specimen shown in Figure 21. A fine inner crack was located at the corner of the end of this specimen, 1.5 mm away from the corner edge

and 2.5 mm long along the shear band. It is at an angle of about 55° with the deformation axis (Figure 26), and was clearly caused by shear. Another crack was in the hoop area, 3mm long and propagated from the free surface towards the center (Figure 27). Before sectioning, this crack was at 45° with the cylinder axis at the free surface.

Free surface cracks have been described in Section 4.2.2. The local strains (in terms of aspect ratio) were measured adjacent to the crack tips of both cracks. The results are given in Table 6, and micrographs of the crack tips are shown in Figures 28 - 30.

From the table, we can see that the local strain at the crack tips was higher than that adjacent to the crack tips.

4.2.5 Free-Surface Strains

Free-surface strain is the strain at the bulged surface of a deformed specimen. The fracture locus can be plotted by the axial and circumferential true strains at the free surface where the crack initiated. Such a fracture locus is called the "forging limit diagram" [6], and is used to predict the forging limit of the process. Although this is a rough evaluation and not generally applicable as described in the introduction, the forging limit diagrams were still made for comparison with the criterion based on local strain.

Specimens of ferritic nodular cast iron were machined into six sets with the same diameter (15 mm), but different lengths (i.e., 12, 15, 18, 21, 24 and 27 mm) and painted with a blue steel dye on a free side surface. A 3mm x 3mm grid was marked on the equator of the painted surface of each specimen as a gauge band. The specimens in each set which had the same

length were compressed by different amounts until cracking occurred. Then the free-surface strains were measured from the deformed grids.

The axial and circumferential true strains on the barrelled surfaces were found using the following equations:

$$\text{axial } \epsilon_z = \ln (l/l_0)$$

$$\text{Circumferential } \epsilon_o = \ln (w/w_o) \text{ or } \ln (D/D_o)$$

where: l_o and l are the initial and final gauge lengths, w_o and w are the initial and final gauge widths, and D_o and D are the initial and final diameters (see Figure 31).

The results are presented in Figure 32.

4.3 Tension Test

The tensile test specimens and their dimensions are shown in Figure 33. Two surfaces were machined symmetrically on the cylindrical specimen, then polished. One of the surfaces was marked over 32 mm length with a 2mm x 2mm grid for reference measurements.

The test was carried out on an Instron machine with cross-head speed of 0.05 in/min. The stress-strain curve is shown in Figure 34. A small degree of necking occurred before breaking. The difference in diameter between the necked (8.80 mm) and unnecked (9.45 mm) parts was 0.65 mm. This can be seen clearly on the stress-strain curve (Figure 34). However, the fractured surface in Figure 35 shows that it is still a brittle fracture. Some specimens were unloaded during necking at point A (Figure

34). Such a deformed specimen is shown in Figure 36 with the corresponding micrograph in Figure 37. Polished surfaces were examined in both the optical and electron microscopes for the specimens which were unloaded during "necking". No cracks were seen, because the specimen broke precipitously.

The true stress-strain curve in Figure 38 shows that the elongation of specimens of annealed nodular cast iron was about 19% (in the 32mm gauge length) with a small degree of necking. The stress-strain curve in Figure 34 shows 21% elongation in the same specimen. The deformation of nodules was also measured as the aspect ratio b/a . The average value for 51 nodules in Figure 37 was found to be 0.68 with a standard deviation of 0.08.

The corresponding average elongation of the nodules was 23 ($\pm 6\%$) calculated by equation (11). This value was in good agreement with the macro-elongation, (21%) which was measured from the change in gauge length.

4.4 Bending Test

A prepared bending-test specimen is shown in Figure 39. Its dimensions were 7.80 x 11.70 x 72.0 (in mm). Grids of 2mm x 2mm were marked on one of its polished lateral surfaces. The three-point bending tests were carried out on an Instron machine using a cross-head speed of 0.2 in/min and a maximum load of 1450 lb. Some specimens were unloaded immediately at the onset of cracking. The results showed that the specimens could be bent as much as 70° before crack propagation, i.e., bent from 180° to 110° (Figure 40). In the bending area, the grids were deformed into

part of a ringlike shape, the lines in the longitudinal direction had become arcs and the lines in the transverse direction now had an angle of 8.7° between each other. The deformation changed from compression near the inner radius to tension near the outer radius. The macro-deformation was determined by calculating the length of the arcs and comparing with the original grids. The results are shown in Figure 41.

In order to measure the local strain distribution, one line of grids in the bend area was cut off from the specimen, polished and lightly etched with 2% Nital, then a micrograph was taken as shown in Figure 42. Additional micrographs at (100x) were taken for the whole area to permit a map to be made from those micrographs Figure 43. It can be seen clearly that the nodule cross-section changed from ellipse $\rightarrow$ circle $\rightarrow$ ellipse as dictated by the local strain. It should be noted that while the lower elliptic nodules were perpendicular to the longitudinal direction of the unit arc, the top elliptic nodules were aligned parallel to the direction of the arc. Local strains were calculated by measuring the aspect ratio (b/a) of nodules and computing the statistical variance. An area 100 mm wide along the radius in the center of (Figure 43) was chosen for measurement, and the average aspect ratio was calculated from the nodules in every 10mm x 100 mm area along the radius. The results are shown in Figure 44. The maximum deformation occurred at the outer radius and at the bend of the inner radius. The aspect ratio was found to be 0.66 at the outer radius, corresponding to 24% elongation. At the inner radius the aspect ratio was 1.64, or -28% elongation in compression. As shown in Figures 41 and 44, there is a neutral plane about 2.4 mm in a radial direction away from the node of the bend. The specimen is in compression below this plane and in tension above this plane.

The variation of deformation with distance from the node of bend also can be calculated from the aspect ratio by equation (5) in section 3.3. The results are shown in Figure 45 and compared with the macro-deformation in Figure 46. The apparent small difference between the macro-with micro-deformations may depend on the accuracy of measurement, the regularity of the nodules and of the matrix, etc. It is seen that the deviation is most marked in the compression half of the sample. The reason for this is not clear and may be associated with the different compressibility of the graphite nodules in comparison with that of the matrix. However, the difference is not of major significance for the test results.

The crack initiation and propagation, shown in Figure 47 were observed from the specimens which were unloaded at the onset of crack initiation. The crack occurred at the surface of the outer radius and was perpendicular to the tensile direction, i.e. in the longitudinal direction. The crack started at the edge of the specimen (Figure 40) because of the stress concentration, and propagated by breaking the bridging of the matrix and linking up the nodules along the direction where the nodule density was the greatest. In general, the local strain at the crack tip was higher than that adjacent to tip (Figure 47). The local strains were measured, giving average values of aspect ratio 0.47 at the tip and 0.59 adjacent to the tip.

4.5 Compression Test at Elevated Temperature

Some compression tests were also carried out at elevated temperatures on a Gleeble machine in CANMET. Cylindrical specimens of 10mm diameter x 20mm length were used because of the capacity of the machine.

Specimens were heated quickly by electric resistance and the temperatures were controlled automatically by the machine. The procedure was as follows: first, specimens were heated to the required temperature in 10 or 15 seconds, and kept at that temperature for 10 seconds to ensure temperature uniformity. Then the specimens were compressed at constant temperature in about 0.5 min. Finally the specimens were allowed to cool down to about 200°C and then water cooled to room temperature. The whole process was done in a chamber which was first evacuated and then filled with argon to avoid oxidation of specimens. The deformation process could be clearly seen through a thick glass window. The reduction value at which cracking started was determined by repeating the experiment with various amounts of applied reduction, as with the compression tests at room temperature. The results are shown in Table 7.

These experiments showed that annealed nodular cast iron could be forged to more than 70% reduction (the limit of the Gleeble machine) at 700°C without cracking. As cast nodular cast iron at 650°C could be forged to 62% reduction with crack initiation, and austenitic nodular cast iron at 550°C was forged to 47% with cracking. There is no doubt that nodular cast irons can be forged at high temperature. It has been reported by Spretnak and his coworkers that the forging range is approximately 900° - 1065°C [4]. Forging of nodular cast iron can profitably be used for industrial applications; for example, in gear fabrication.

Comparing these results with those for cold forgeability, we find that the forgeability of nodular cast irons increased with increasing temperature due to stress relaxation, recovery and recrystallization. However this is a complicated phenomenon. In this experiment the specimens were compressed under constant temperature and the whole process (from

heating up to finishing compression) took a short time (about 1 minute). Further experiments on the Gleeble machine should be conducted under conditions from just above room temperature (100°C) to the recrystallization temperature of the matrix material under study, and for various holding times at each temperature. At high temperature, nodular graphite could diffuse into the matrices, causing a possible difficulty for the local strain measurement.

5. RESULTS AND DISCUSSION

Good nodularity and suitable deformation properties of nodular cast irons make them desirable as test materials for a forgeability study based on local strain measurements.

Nodularity (nodule shape, size and distribution) is determined by two main factors: melt treatment and cooling rate during solidification. These were effectively controlled by investment casting in this study.

The deformation properties of nodular cast irons were generally evaluated by compression testing. The cold forgeability, as shown in Table 4 ranged from 35% to 60%. Since the nodular cast irons could be considerably deformed before cracking at room temperature, they are suitable for the forgeability study.

Our results show that the deformation properties of a nodular cast iron depend mainly on the type of matrix. The nodules behave as incompressible cheese-like regions in the matrix, and deform easily. Some graphite nodules were squeezed out from the surface or subsurface of ferritic nodular cast iron specimens because of the ductility and the low strength of the matrix, and the ductility of the nodules.

We have proven, both theoretically and experimentally, that the nodule shape will change from spherical to oblately ellipsoidal during deformation. Local strains can be determined by measuring the aspect ratio b/a of the deformed nodules in the sectioned specimens. The aspect ratio may be considered independent of sectioning as long as the sectioning is parallel to the axis of compression. The relation between aspect ratio and reduction was derived, providing a direct comparison between the macro- and micro-deformation. The results in compression, in tension, and in bending tests show a good agreement between the macro- and micro-deformations. Thus, we can use this method for the study of deformation distribution (such as dead zones, shear bands, hoop zone and centre large deformation zone) and fracture, based on local strain measurements. It will also be possible to find a criterion for the forgeability generally applicable to forging processes.

In the tension tests, the maximum elongation of annealed (ferritic) nodular cast iron without cracking was about 21% in gauge length. The aspect ratio of the nodules in the same specimen was found to be about 0.67, with a standard deviation of 0.08, corresponding to an average elongation of 23 (± 6)%. This is in good agreement with the macro-elongation. The large uncertainty in the micro-elongation is due to the influence of irregular shaped nodules on the ratio. The scatter could be improved by avoiding measurement of the irregular shaped nodules. It should be noted that the aspect ratio $b/a = 0.67$ may be taken as a criterion of the maximum local strain of the annealed (ferritic) nodular cast iron for pure tension.

In the bending test, the annealed nodular cast iron specimens were

bent as much as 70° . A map of the local strain of the bend area was made from an examination of nodule shapes in the enlarged micrographs, and clearly shows the distribution of the deformation. The shape of the nodules varies from the outer radius (ellipses with the major axes in the longitudinal direction of the specimen) to the inner radius (ellipses with the major axes in the radial direction of the bend area). In other words, the deformation varies gradually from tension at the outer radius to compression at the inner radius in the bend area. A neutral plane occurs in the position where the aspect ratio b/a is 1, and is indicated in Figure 44. The maximum deformation was about 24% in tension (at the surfaces of the outer radius) and about -28% in compression (at the inner radius in the bend area). The tension deformation is of particular interest here because it causes cracking. In the bending test the maximum tension deformation was 24% (measured by the aspect ratio), which is close to the result determined from gauge length changes. This is also close to the maximum elongation (23%) in the tension test. The maximum tensile deformation may be greater than 24%, because the crack started at a marked line (perhaps due to stress concentrations). It would have been better to make grids on a surface by printing rather than mechanically inscribing.

The macro- and micro-deformation distributions in the bending area are compared in Figure 46. The micro deformation curve is shown by small dots and the macro deformation by square symbols.

The scatter of dots about the curve of micro-deformation is mainly due to the variation in roundness of the original nodules. The difference between the curves for micro- and macro-deformation is due to the precision of the measurements, the regularity of nodule shape and the relationship between the deformation of nodules and that of the matrix. The deviation

may be reduced by making good nodules in nodular cast iron, avoiding measurement of irregularly shaped nodules, improving the accuracy of measurement and finding the relationship between the deformation of nodules and the matrix.

There will generally be some deviation between the macro- and micro-deformation curves, but the deformation measured statistically by aspect ratio will be more reliable than that measured by gauge length, especially for irregular-shaped objects.

In the compression test, the frictionlessly-deformed specimen showed uniform deformation without different deformation zones. This makes a comparison of micro-deformation with macro-deformation possible. The micro-deformation measured by the aspect ratio b/a was 26 (± 2)%. This agrees well with the macro-deformation which was 24% in reduction.

In the normal compression test (with friction against the contact surfaces), the deformation is more complicated; therefore a criterion based on local strain measurement for compression test must be defined. Some useful information has been obtained, namely:

- a) Deformation zones, such as dead zones, shear bands, small deformation zones (in the hoop area) and large deformation zones (in the centre) can be clearly identified at a magnification of about 100x to 200x by the nodule shape and changes of orientation in the matrix. If it is needed, a large map of the whole section of a specimen can be made to show the deformation. The local strains in these zones can then be measured from a statistical analysis of the changes in aspect ratio b/a and the orientation of the major axis, as shown in Table 4. Also, the width of a shear band can be measured. Moreover, the

deformation distribution and local strains at any area of interest can be shown and measured in this way.

- b) Cracks can be studied for the compression test. However, cracks will only occur under tensile or shear stresses, i.e. if the lateral body forces are not balanced. In such cases cracking may occur, but when it does it will tend to be associated with an external surface. For example, a crack would not occur in the center of a sample, even though the deformation was more than 50% in the center of the specimen, while the same sample would crack at a free surface after a reduction of 36%. This means that a forging criterion based on local strain measurement must be concerned with two factors: local stress conditions and aspect ratio. The tendency to crack will increase with decreasing aspect ratio only under tension and shear stress conditions.

In the particular case of this experiment two cracks were found in the specimen of austenitic nodular cast iron after a reduction of 38% in compression: one in the hoop area and another in the shear band. The basic information for this shear crack was obtained from the sectioned specimen. The position of the shear band was at an angle of 55° with the deformation axis and the width of the shear band was 0.25 mm. The aspect ratio of nodules in the shear band was 0.16. The crack was just in the shear band and the aspect ratio of nodules around the crack was 0.16. The aspect ratio at the crack tip was 0.12, indicating a higher strain than that around the crack, i.e. the local strain at the crack tip was higher than that around crack because of the local stress concentration. The question of whether the aspect ratio can be taken as a criterion for

the shear crack in the shear band for this material is still to be considered.

A forging limit diagram for ferritic nodular cast iron at room temperature (see Figure 32) shows the fracture locus plotted by the axial and circumferential true strains at the free surface where the crack initiated. This may be useful for comparison with the criterion based on local strain and is also useful for practical forging. However a criterion for the hoop tension still has to be found.

Cracks in the bending test and compression test, (e.g. in the shear band or free surface) were studied. A crack will initiate at the weakest place of the material and under the highest tensile stress or shear stress in this location. The crack propagates along grain boundaries in the direction in which the nodule density is the highest by linking up nodules, thereby breaking the interbridges of the matrix. Local strain at or near the crack tips can be inferred from changes in the aspect ratio of the deformed nodules. The results in specimens subjected to bending and compression testing show that the local strains at the crack tip are higher than at any other region in the vicinity, due to local stress concentration at the crack tip and the existence of a plastic zone in front of the tip during propagation. The local strain is lower along the crack than at the tip because the crack occurs abruptly.

6. CONCLUSIONS

- a) Nodular cast iron with good spherical nodules is a suitable modeling material for the study of forgeability, because cracking will occur under certain deformation conditions and the

deformation can be recorded by the change of shape of the nodules. In addition, different forgeabilities can be obtained by changing the matrix. Good nodularity (nodule shape, size and distribution) of nodular cast iron can be produced and controlled by investment casting.

- b) The aspect ratio method can be used for local strain measurement. The advantage of this method is that the aspect ratio is independent of nodule size and sectioning as long as the sectioning is parallel to the main axis of deformation. It is both theoretically and experimentally proven.
- c) The local deformation distribution of any area of deformed nodular cast iron can be determined from a sectioned specimen by observing the nodule shape change in the matrix. A map of deformation distribution of the whole sectioned area can be made from enlarged micrographs of the entire area.
- d) The local strain in any area of interest can be measured by measuring the shape change of nodules in terms of aspect ratio and nodule orientation.
- e) Cracking may also be studied in this way. Basic information such as crack initiation, propagation and local strain at or near crack tips can be obtained.

7. FURTHER WORK

- a) The effect of nodule size and number on the deformation and forgeability of nodular cast iron should be studied, since inclusions can affect the forgeability of materials.

- b) The effect of temperature and strain rate on the forgeability should be investigated.
- c) The forgeability criterion still needs to be expressed in terms of local strain. In particular the influence of volume fraction of nodules and any departures between macro- and micro compressive strain measurements (e.g. Fig. 46) should be examined.

8. ACKNOWLEDGEMENT

The experimental work has been carried-out mainly at Queen's University. However some compression testing and hot-deformation testing was done at CANMET. As a result it is a pleasure to acknowledge the assistance of Mr. W.W. Koch, Dr. J.T. Dowker and Mr. M.W. Letts, who offered invaluable advice on the use of the Gleeble machine and the hydraulic compression tester respectively.

Throughout the project, the advice of Dr. J.J.M. Too has been invaluable.

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in mm

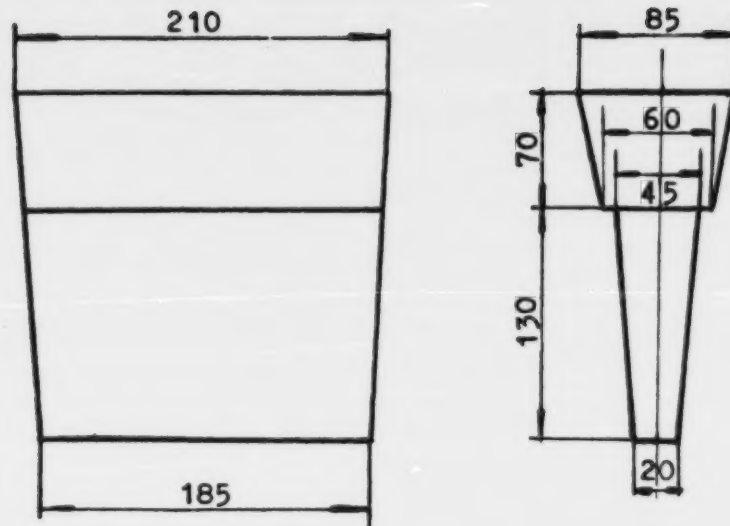


Fig. 1. Keel-Block.



Fig. 2. Wax pattern of ceramic mold.



Fig. 3. Wax patter of ceramic mold.

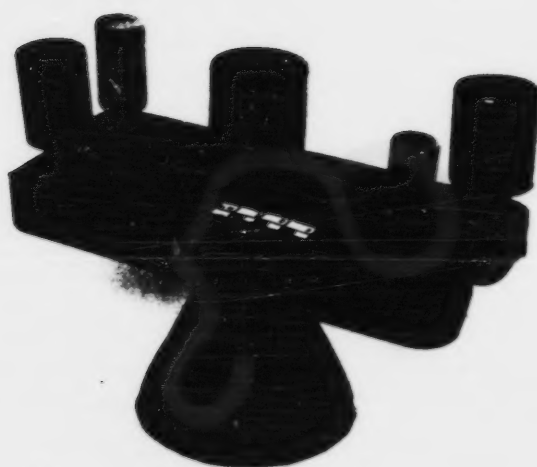


Fig. 4. Wax pattern of ceramic mold for nodular cast iron of different cooling rate.



Fig. 5. Different nodules sizes and numbers from specimens of Fig. 4. Unetched, (100x).

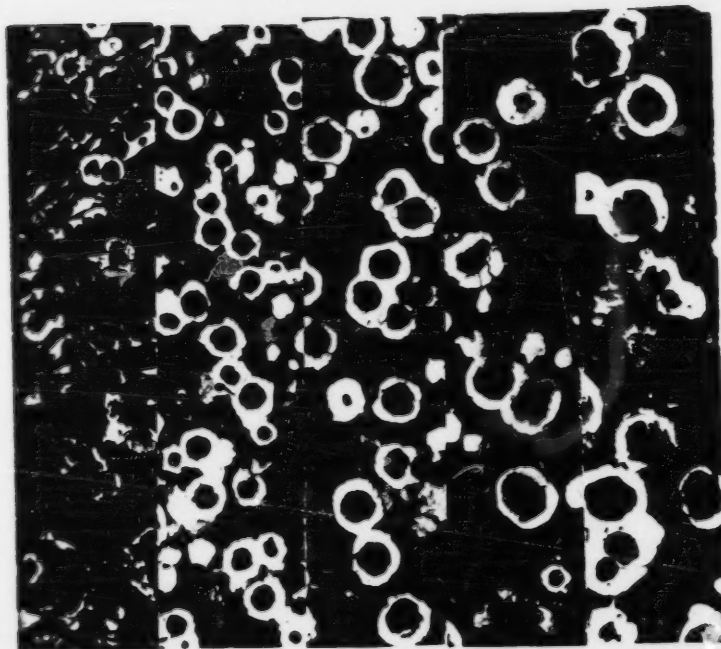


Fig. 6. Different nodules sizes and numbers from specimens shown in Fig. 4. 2% Nital etched (x100).

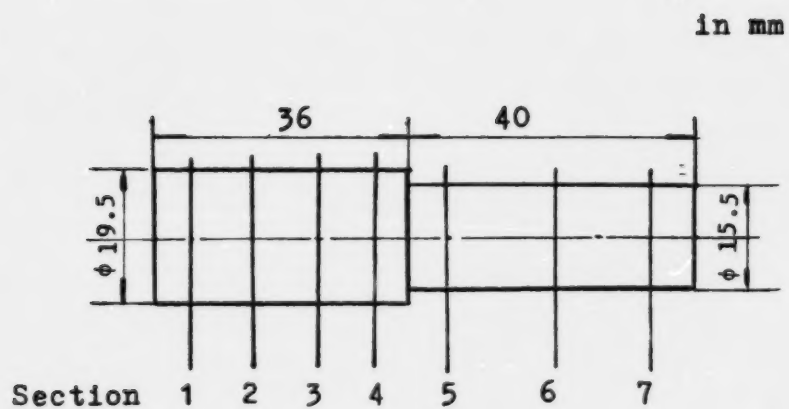


Fig. 7. Cutting sections for checking soundness of castings.

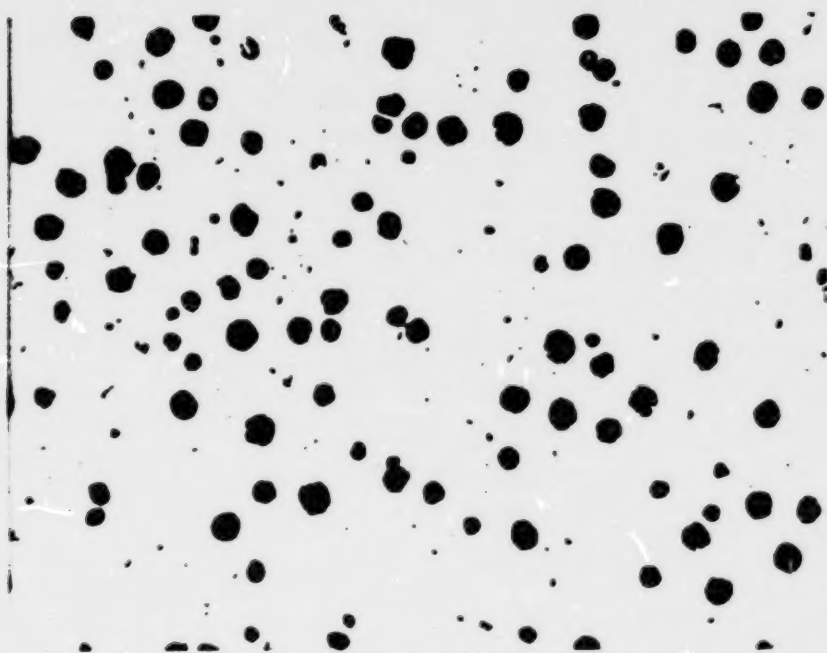


Fig. 8. Ferritic/pearlitic nodular cast iron, unetched (100x).

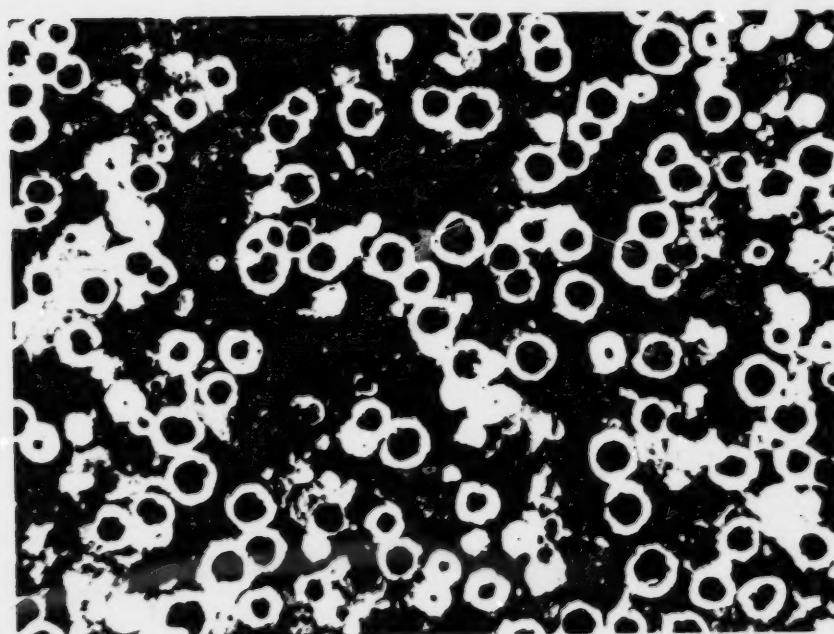


Fig. 9. Ferritic/pearlitic nodular cast iron 2% Nital etched (100x).

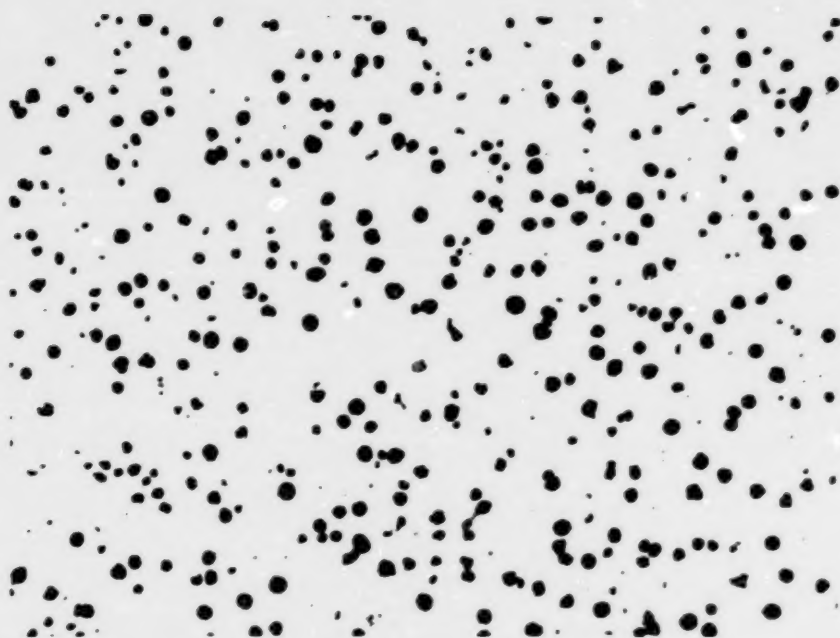


Fig. 10. Austenitic nodular cast iron, unetched (100x).

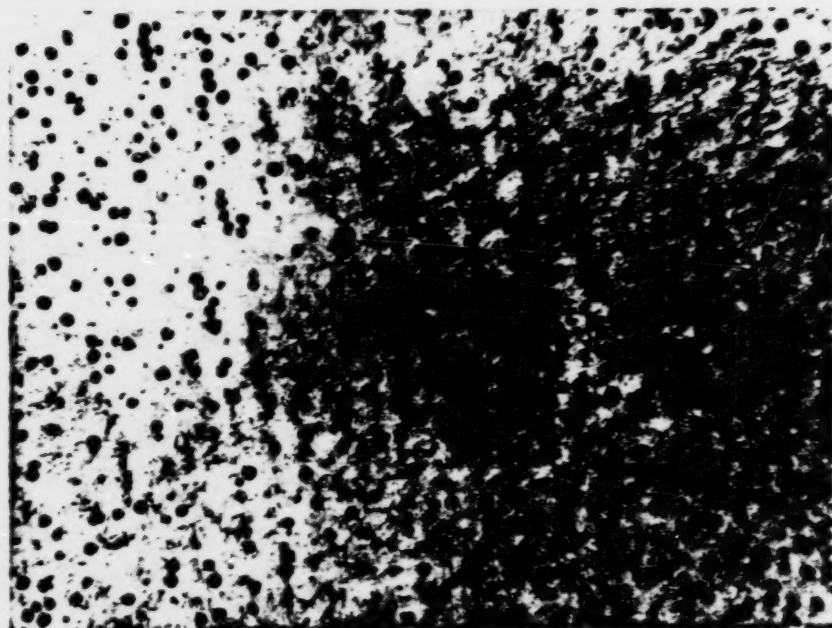


Fig. 11. Austenitic nodular cast iron, etched (100x).

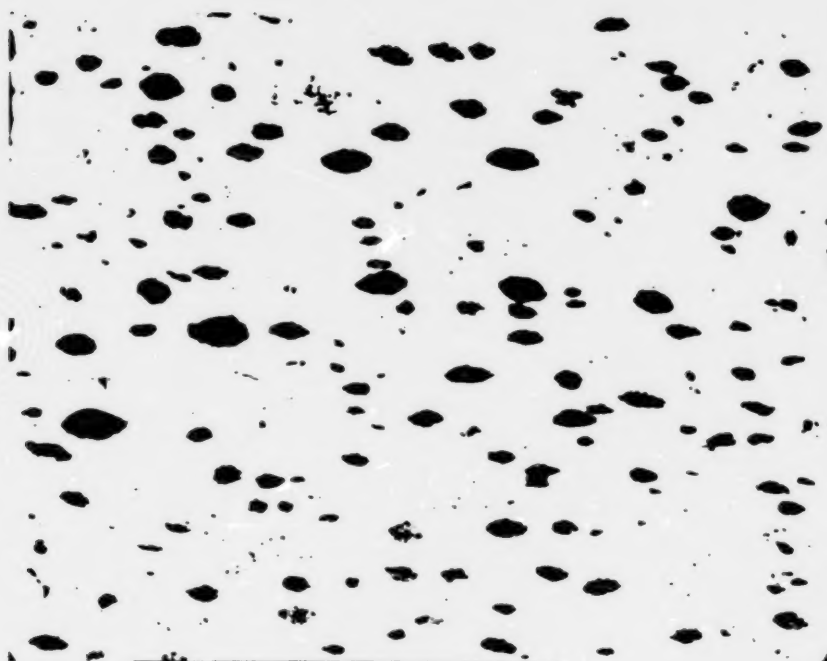


Fig. 12. Shape of nodules becomes elliptical in longitudinal section after deformation. Austenitic nodular cast iron (100x).

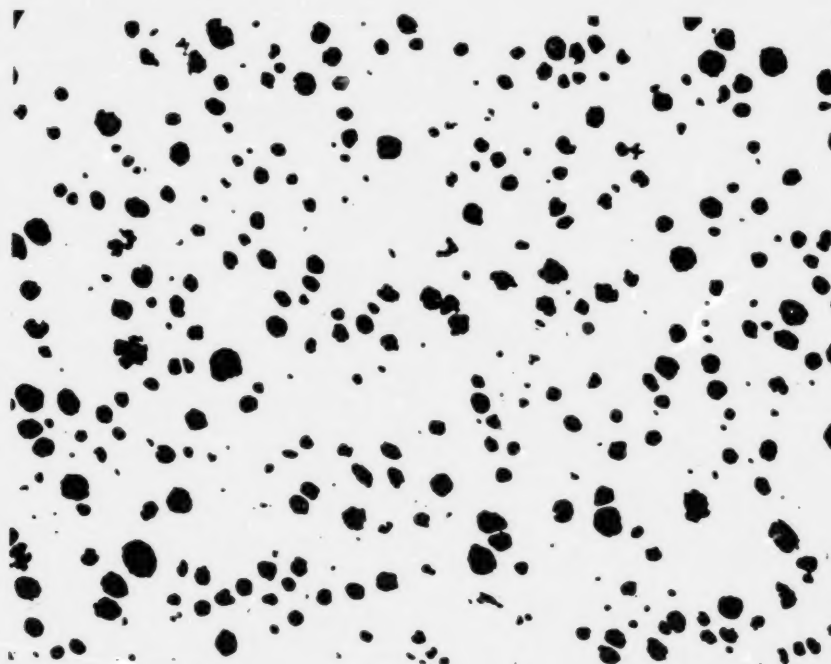


Fig. 13. Shape of nodules remains circular in transverse section after deformation. Austenitic nodular cast iron (50x).

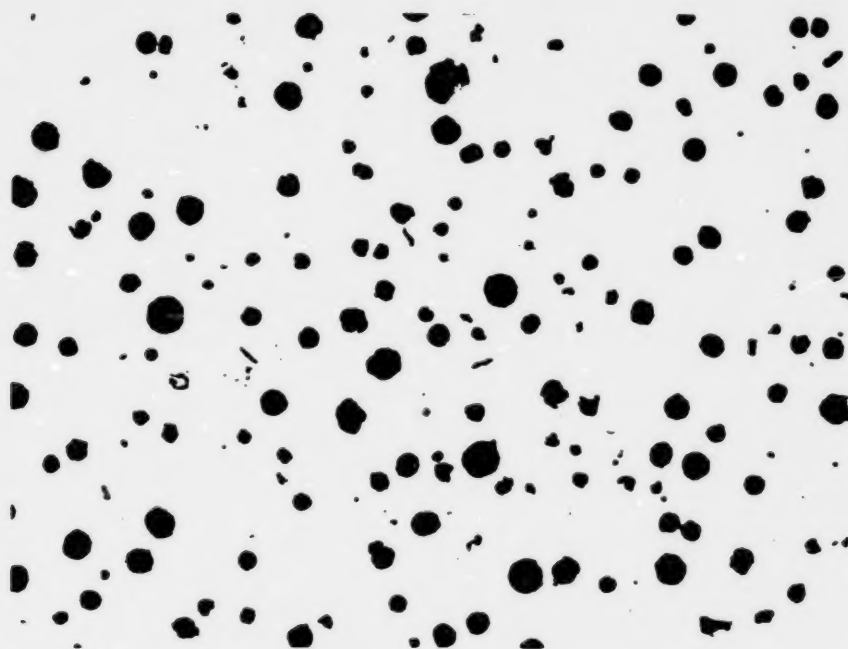


Fig. 14. Pre-deformation structure of austenitic (nodular cast iron) unetched (100x).



Fig. 15. Specimens before and after frictionless compression.

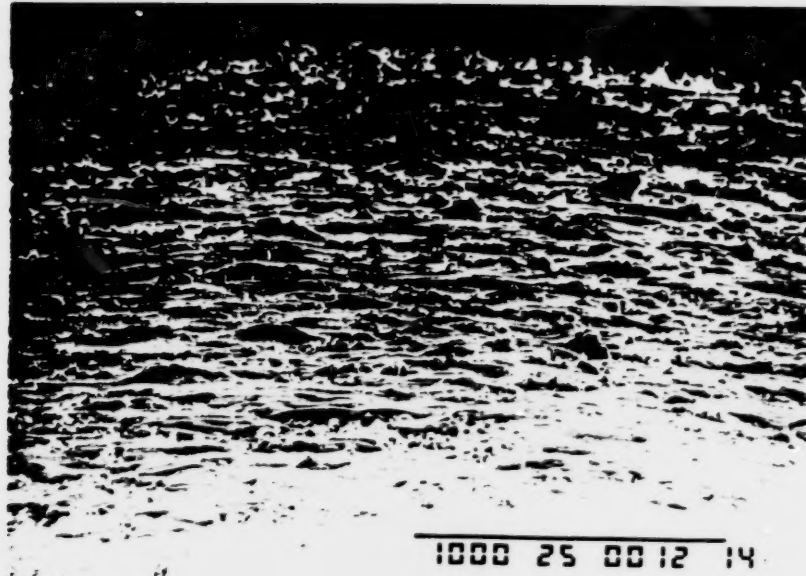


Fig. 16. Deformed surface of ferritic nodular cast iron specimen, SEM (50x).



Fig. 17. Deformed surface of ferritic nodular cast iron specimen, SEM, (350x).



Fig. 18. Graphite extruded out form surface or sub surface of ferritic nodular cast iron specimen (750x).



Fig. 19. Deformed surface of austenitic nodular cast iron specimen (500x).

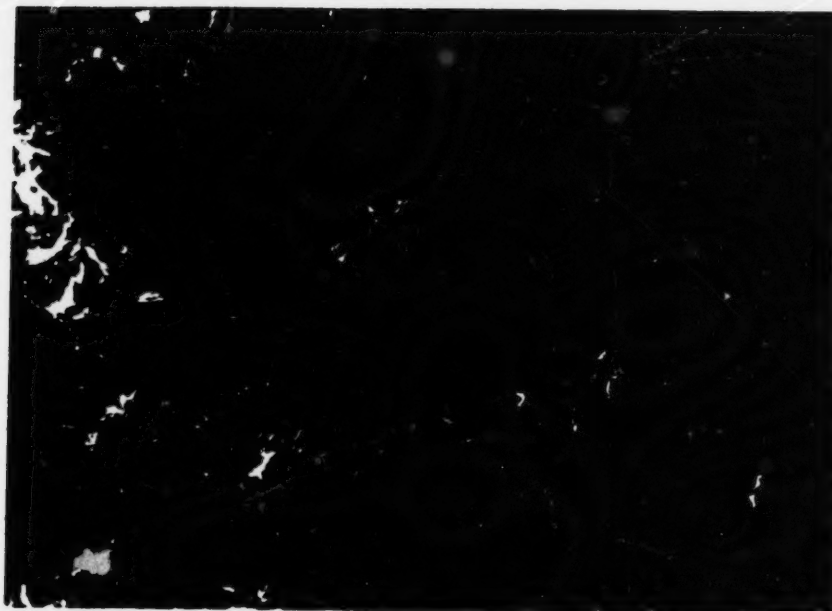


Fig. 20. Surface crack of ferritic nodular cast iron specimen. Crack is at 45° with axis of cylinder, (200x).

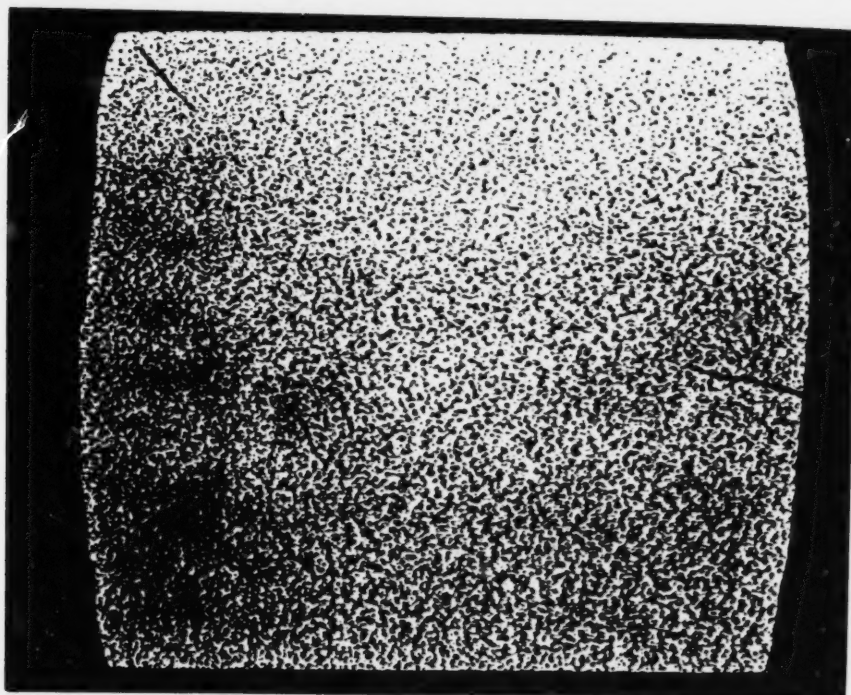


Fig. 21. A micrograph of a longitudinal section of an austenitic nodular cast iron specimen after compressing by 36% in reduction (5.5x).

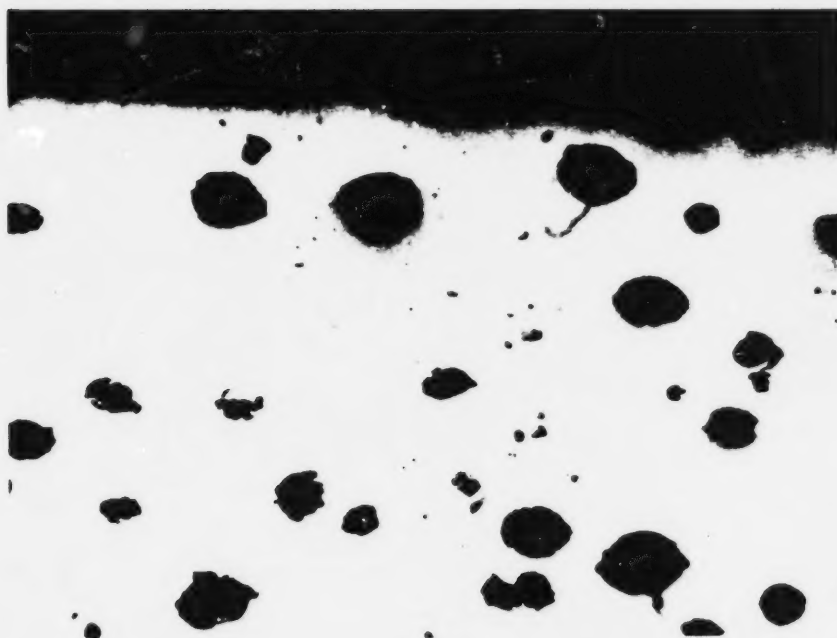


Fig. 22. Dead Zone, $b/a = 0.72$, (200x) austenitic, unetched.



Fig. 23. Hoop Area, (200x), $b/a = 0.34$ austenitic, unetched.



Fig. 24. Centre Area (200x), $b/a = 0.21$, austenitic, unetched.



Fig. 25. Shear Band (200x), $b/a = 0.16$, $\alpha = 55^\circ$, austenitic, unetched.

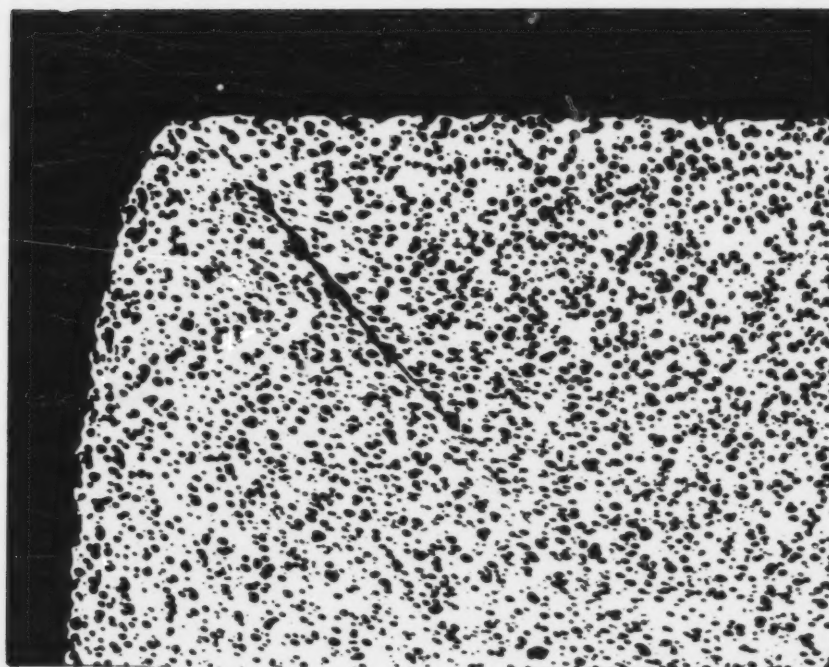


Fig. 26. The crack in the shear band (austenitic) compressed to 38% in reduction, unetched.

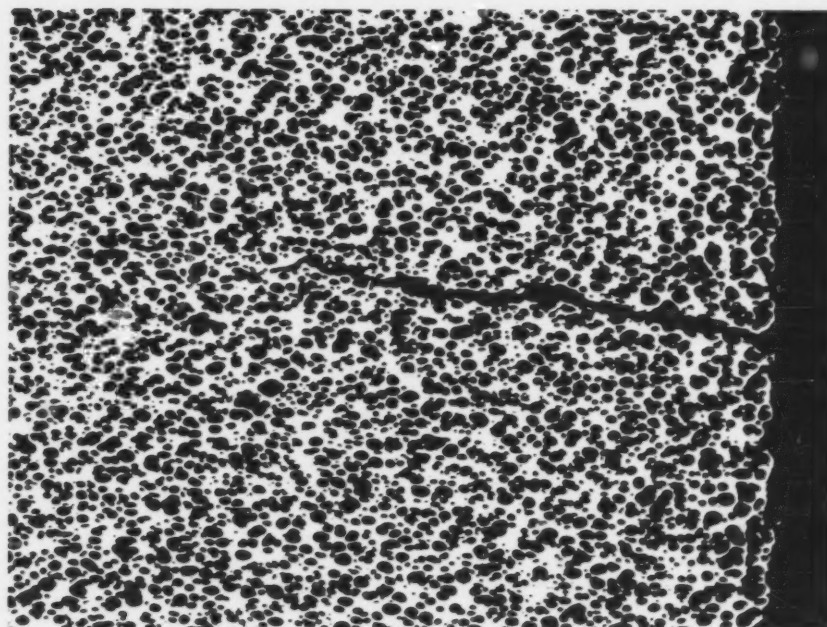


Fig. 27. The crack in the hoop area propagating into the centre (austenitic), unetched.



Fig. 28. The shear crack tip in the center of the specimen (austenitic), unetched, (100x).



Fig. 29. The shear crack tip in the corner of the specimen (austenitic), unetched (130x).

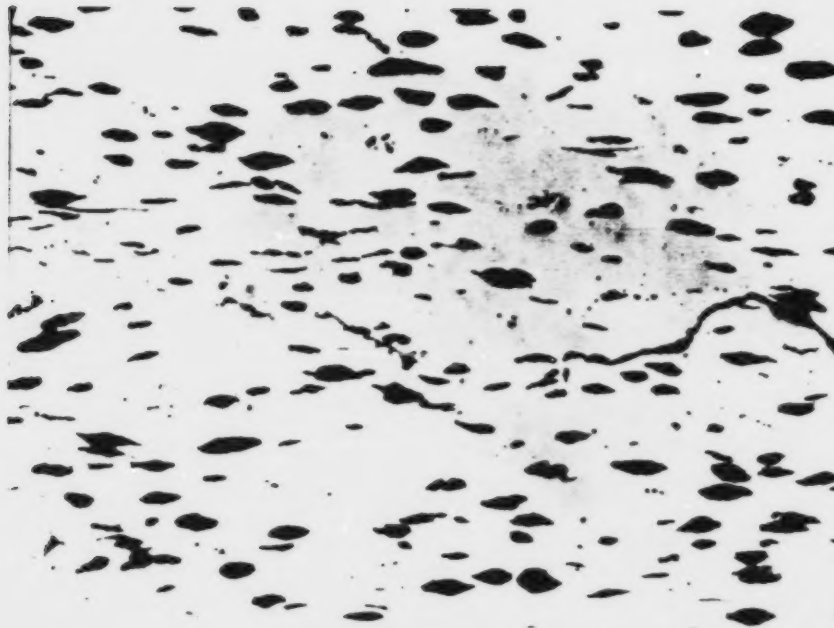


Fig. 30. The Hoop crack tip in the center of the specimen (austenitic), unetched (130x).

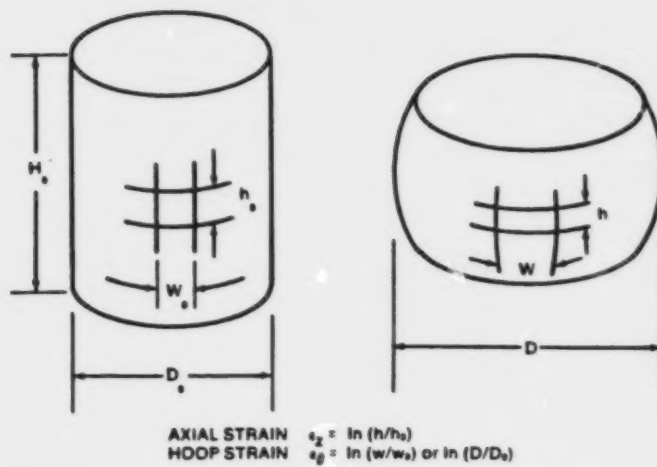
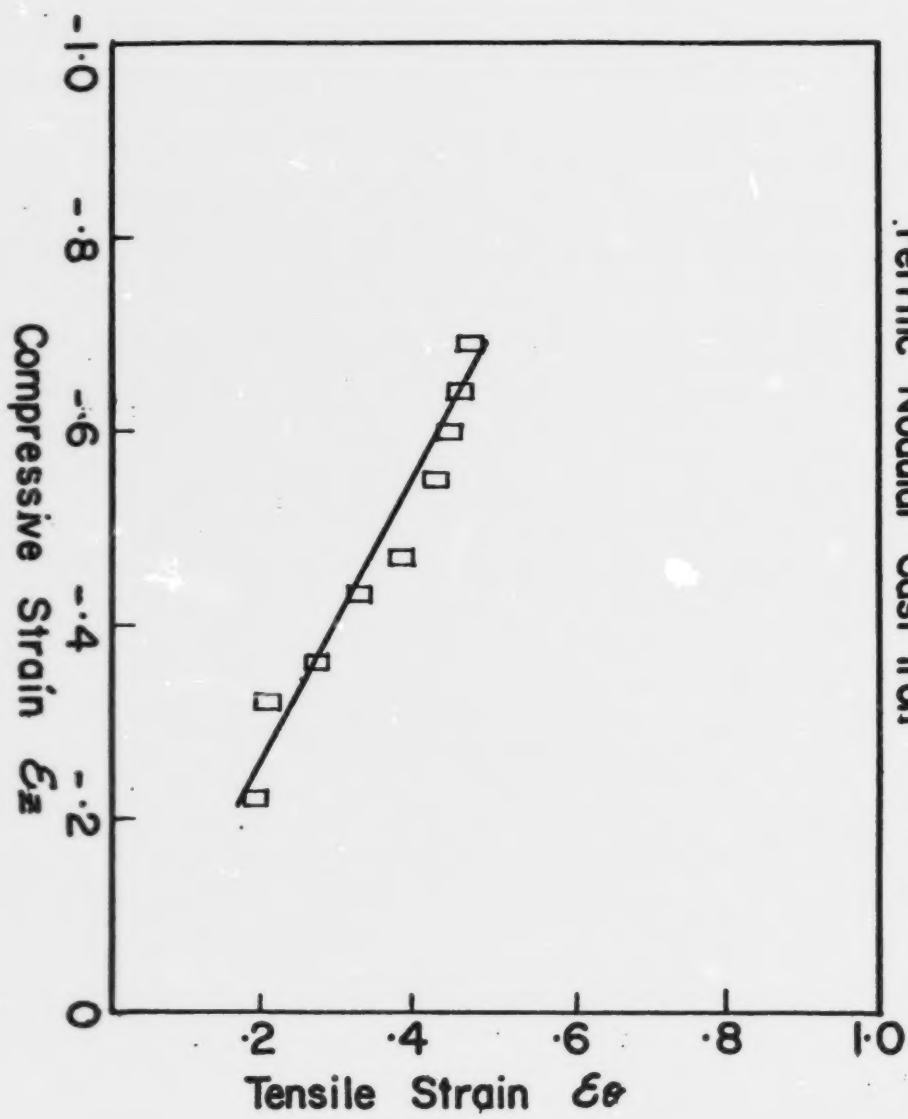


Fig. 31. Grids for strain measurements on upset cylinders.

Fig.32 Strain at Free Surface of Compression Test
Ferritic Nodular Cast Iron



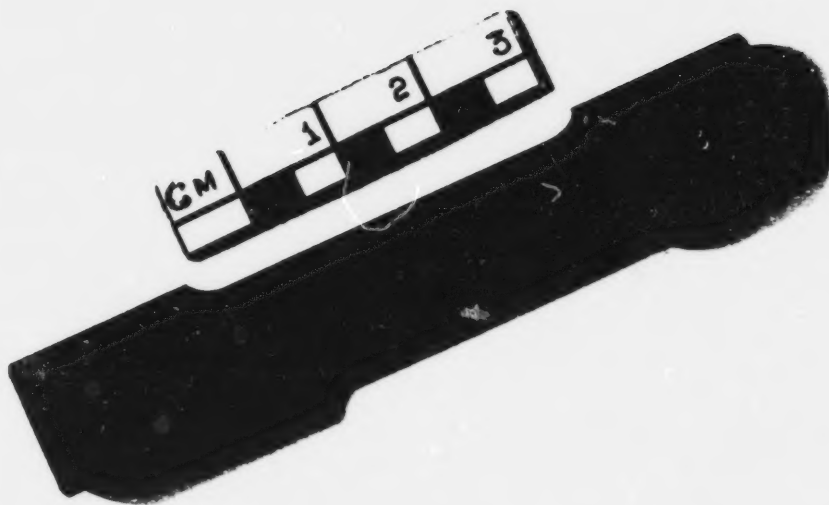
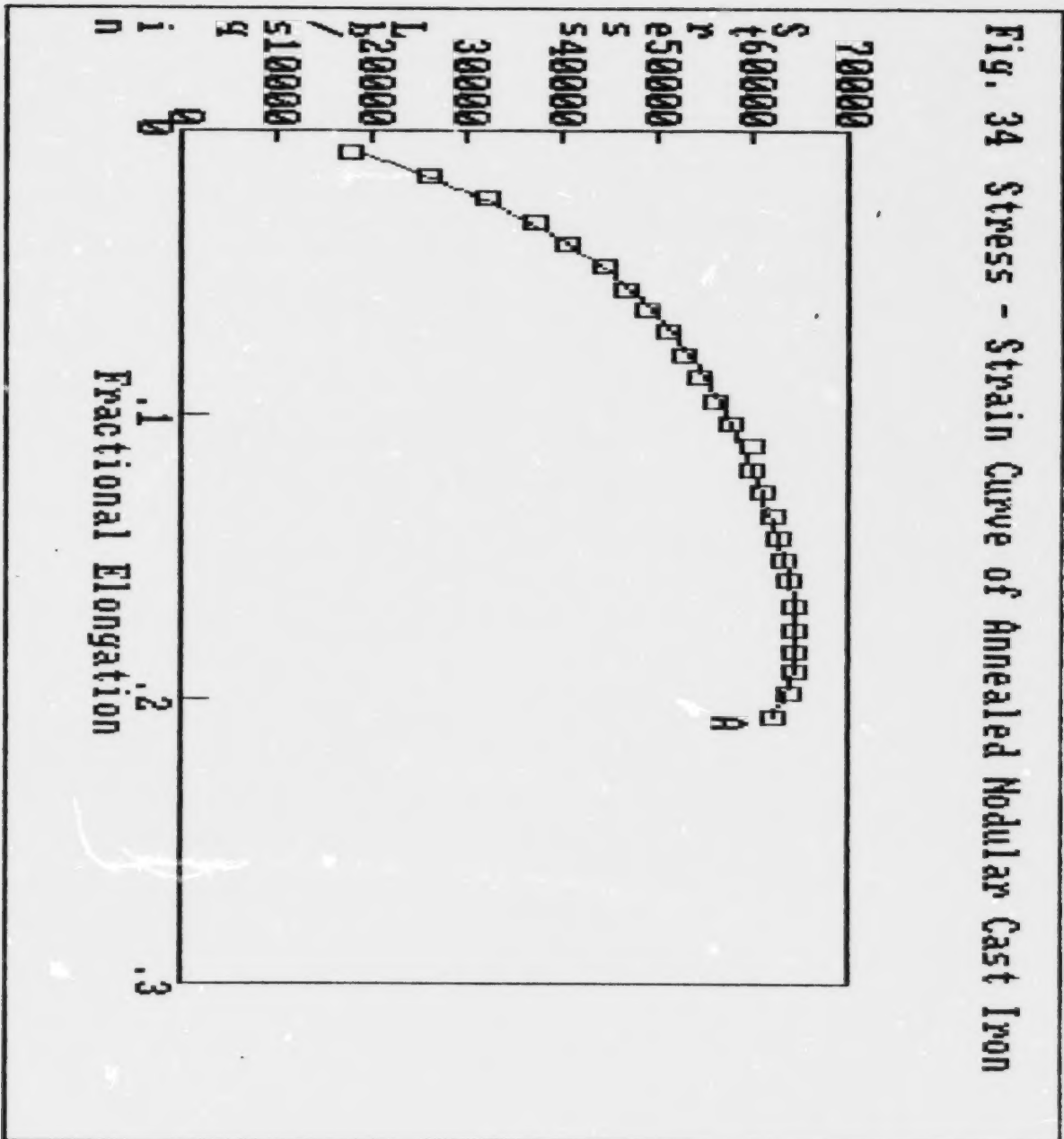


Fig. 33. The specimen for tensile testing.

Fig. 34 Stress - Strain Curve of Annealed Modular Cast Iron



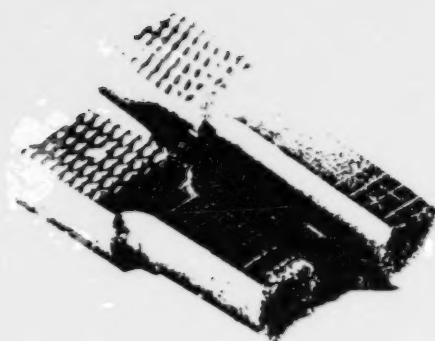
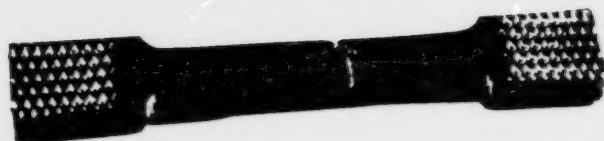


Fig. 35(a) and (b) A fractured tensile specimen.

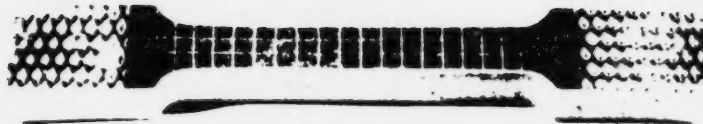


Fig. 36. The specimen unloaded during "necking" (1.25x).

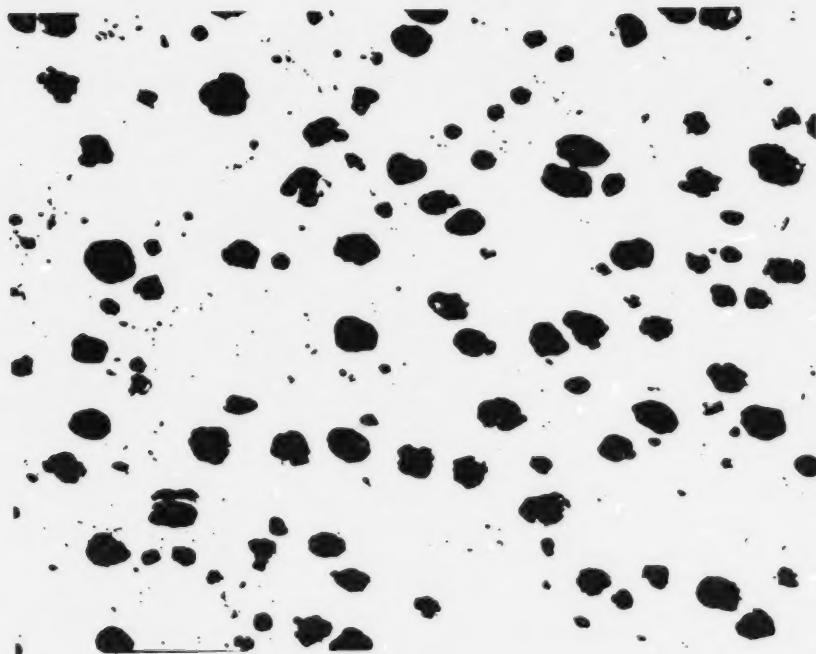
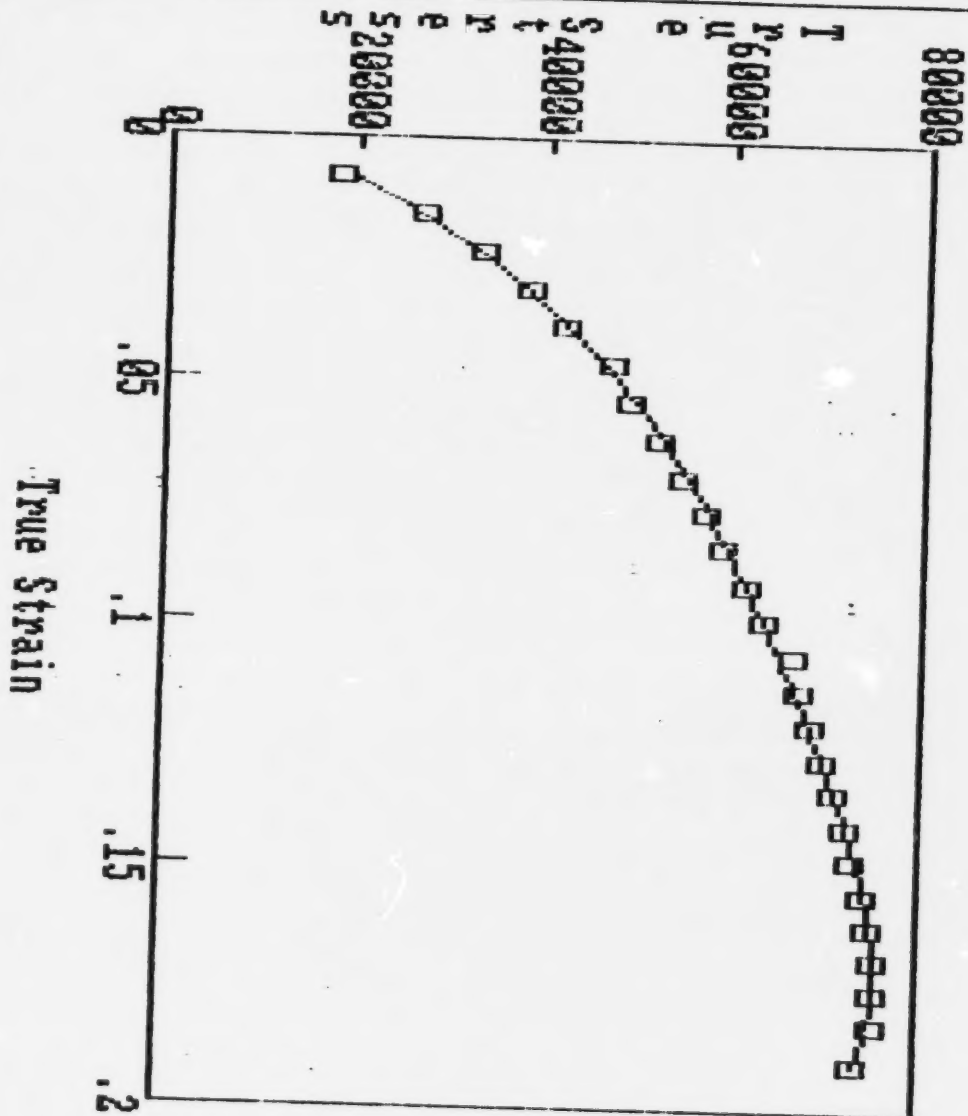


Fig. 37. Micrograph from tensile specimen after deformation.

Fig. 38 True Stress-Strain Curve of Annealed Modular
Cast Iron with a Ferritic Matrix
lb/sq.in.



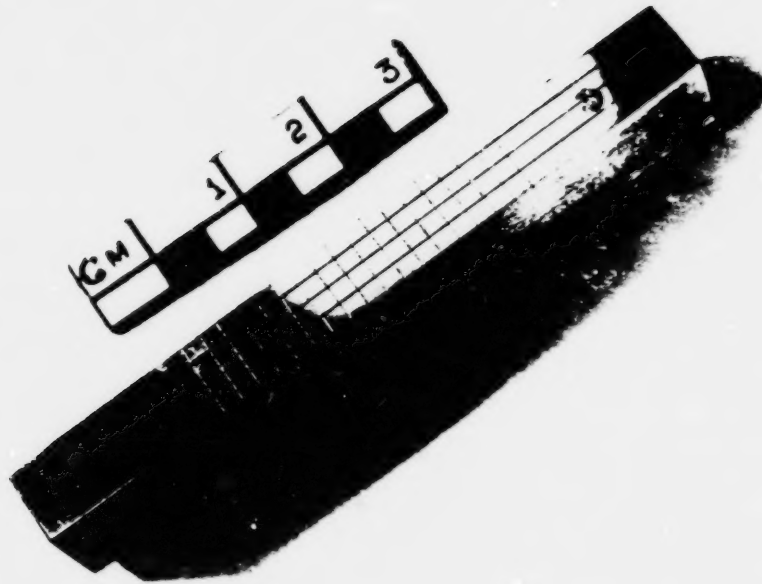
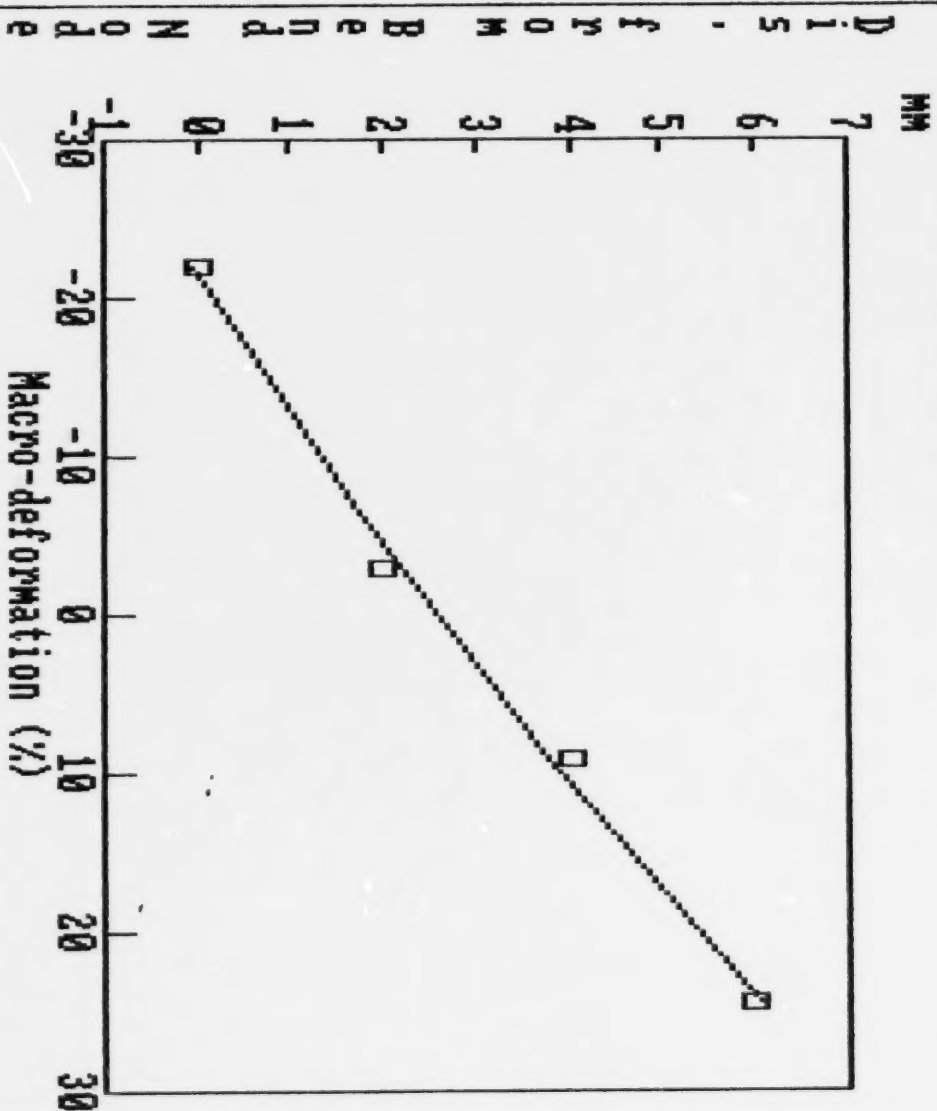


Fig. 39. A bending specimen before deformation.



Fig. 40. A specimen after three-point bending.

Fig. 41 Variation of Deformation with Distance from Node of Bend



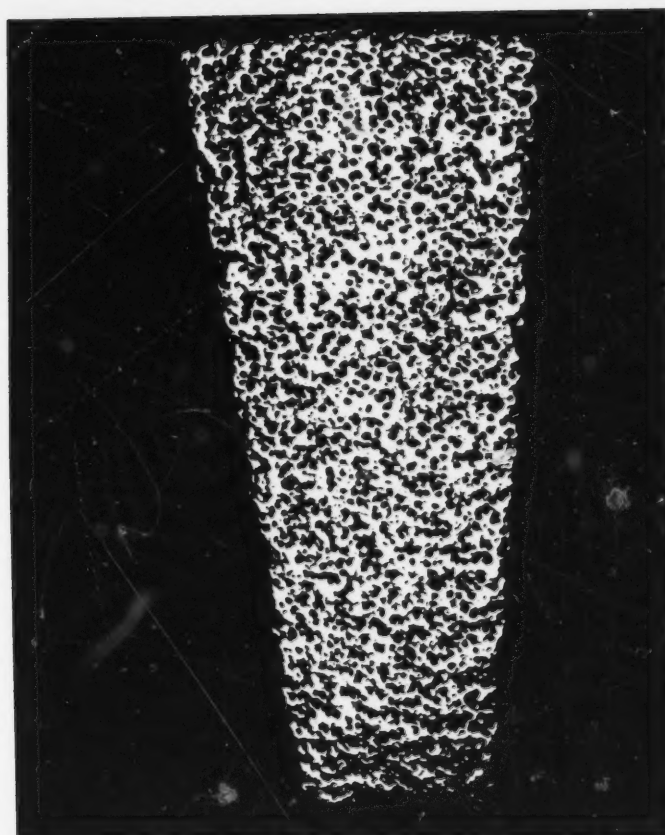


Fig. 42. The macrostructure of the section cut at point A (Figure 40),
1 1/2 mm behind side surface (6x).

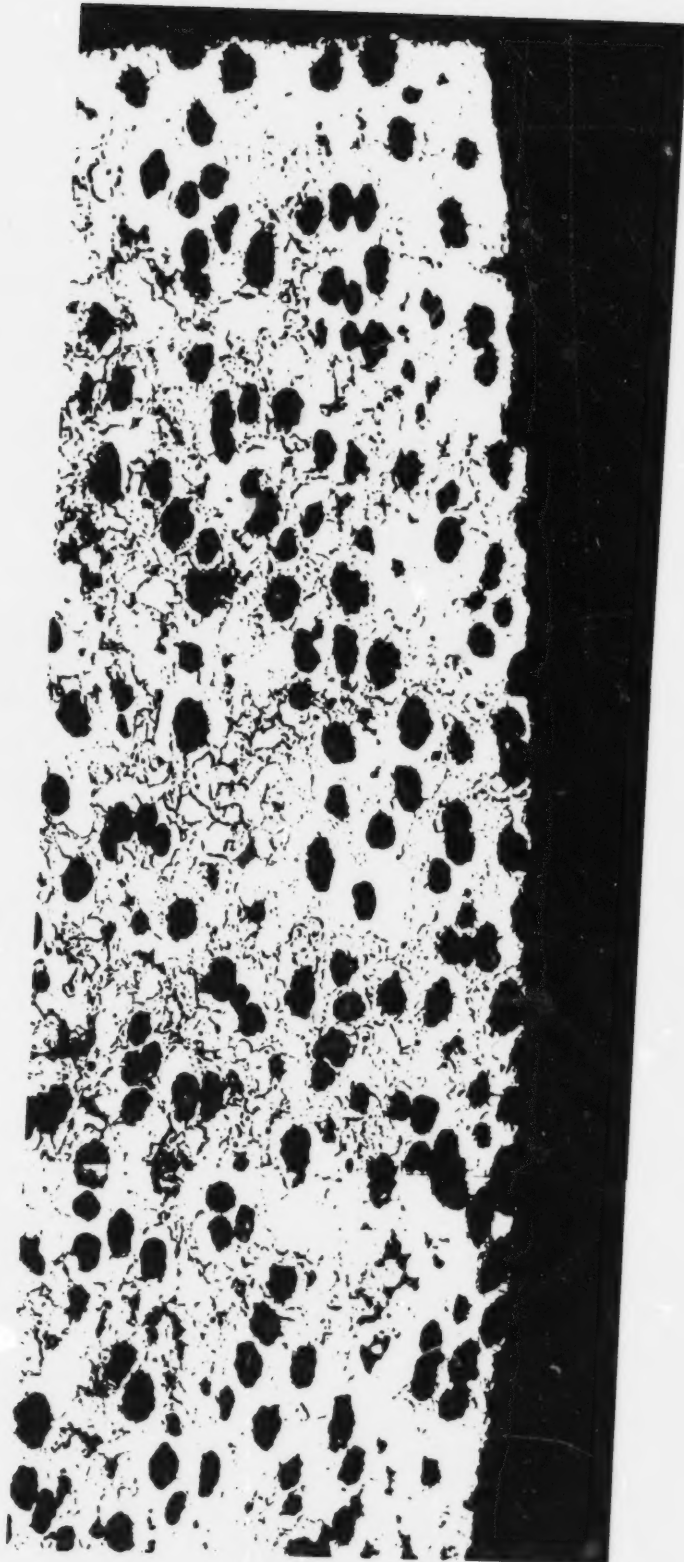
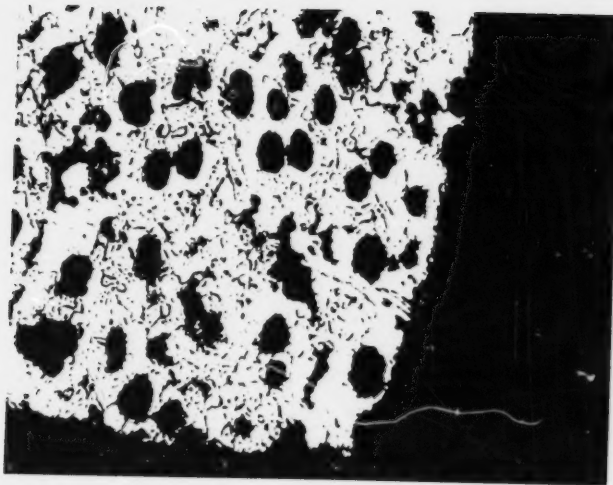
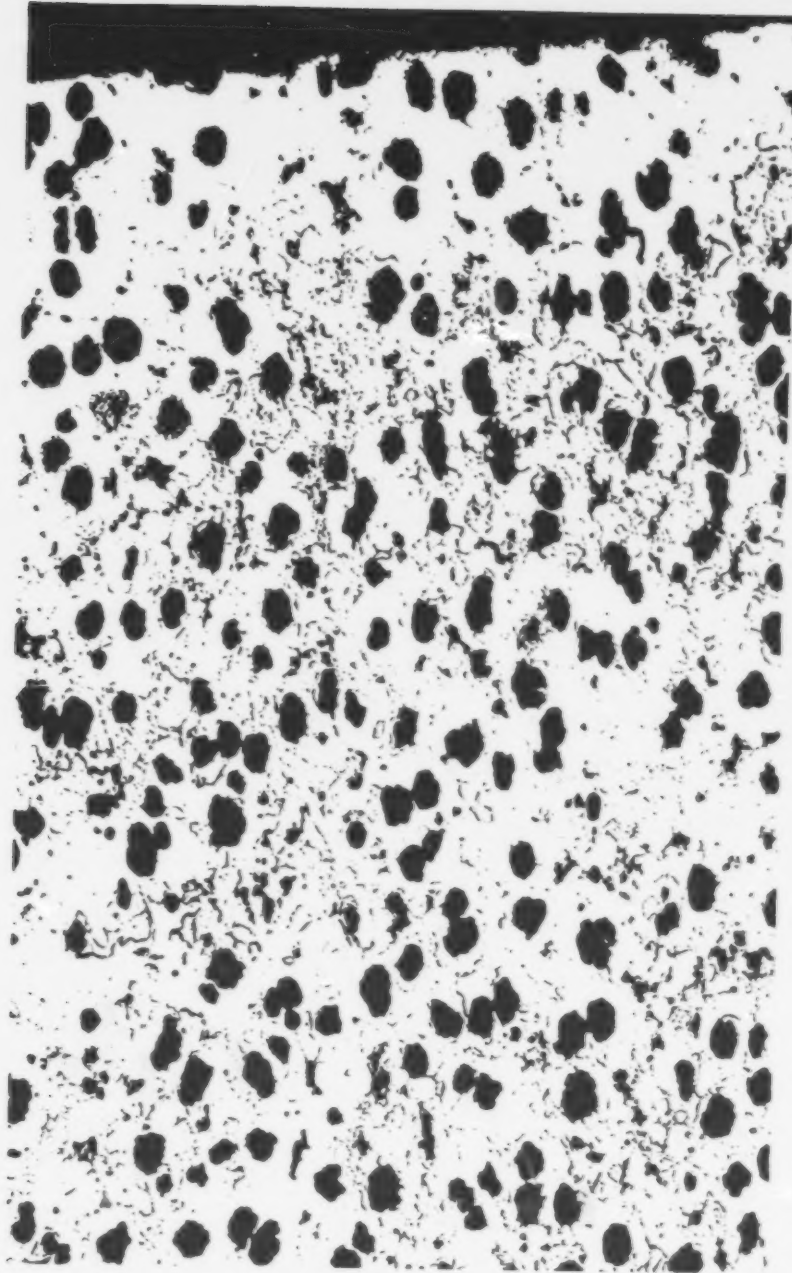


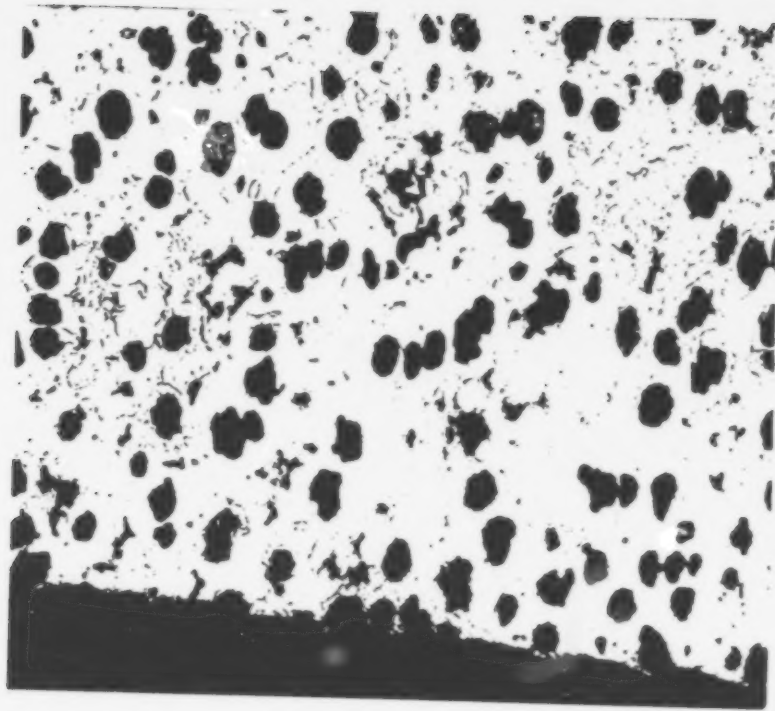
Fig. 43. (1-6) The macrostructure of the bend region (100x).

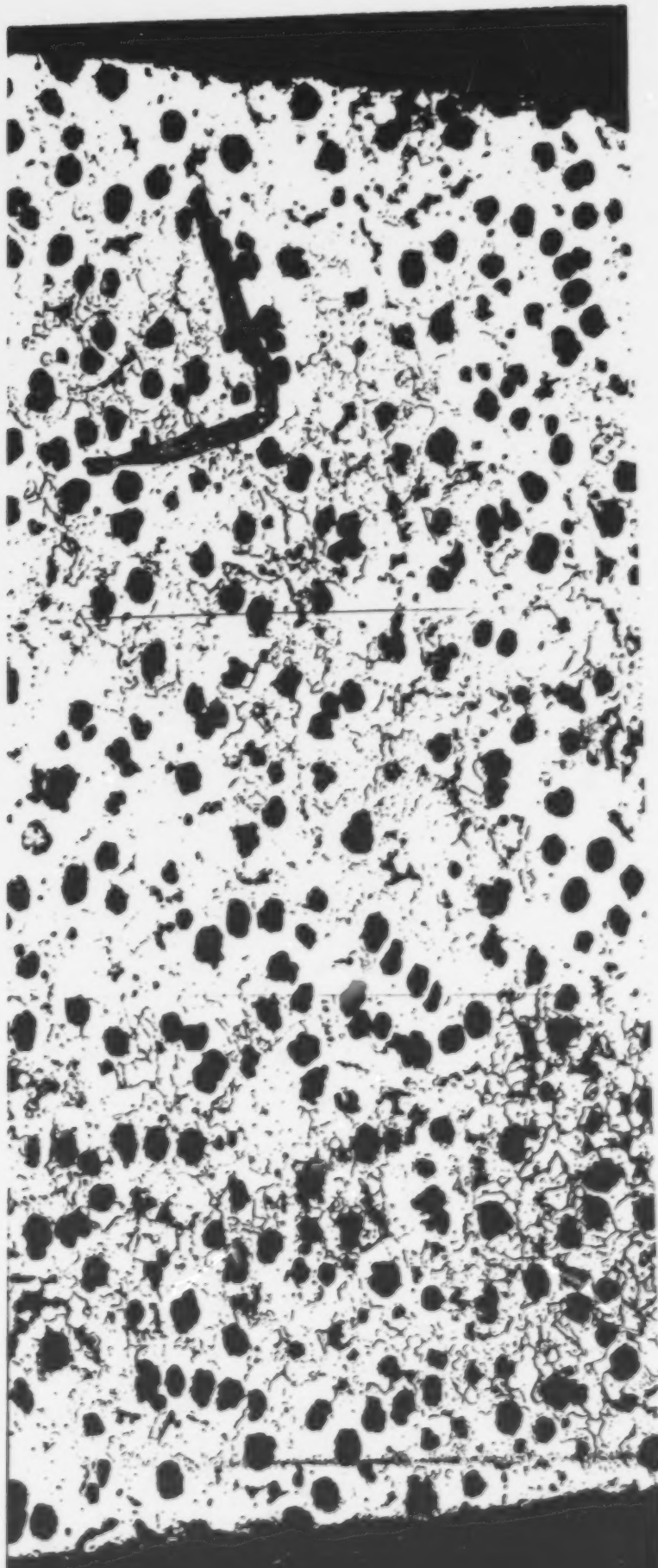


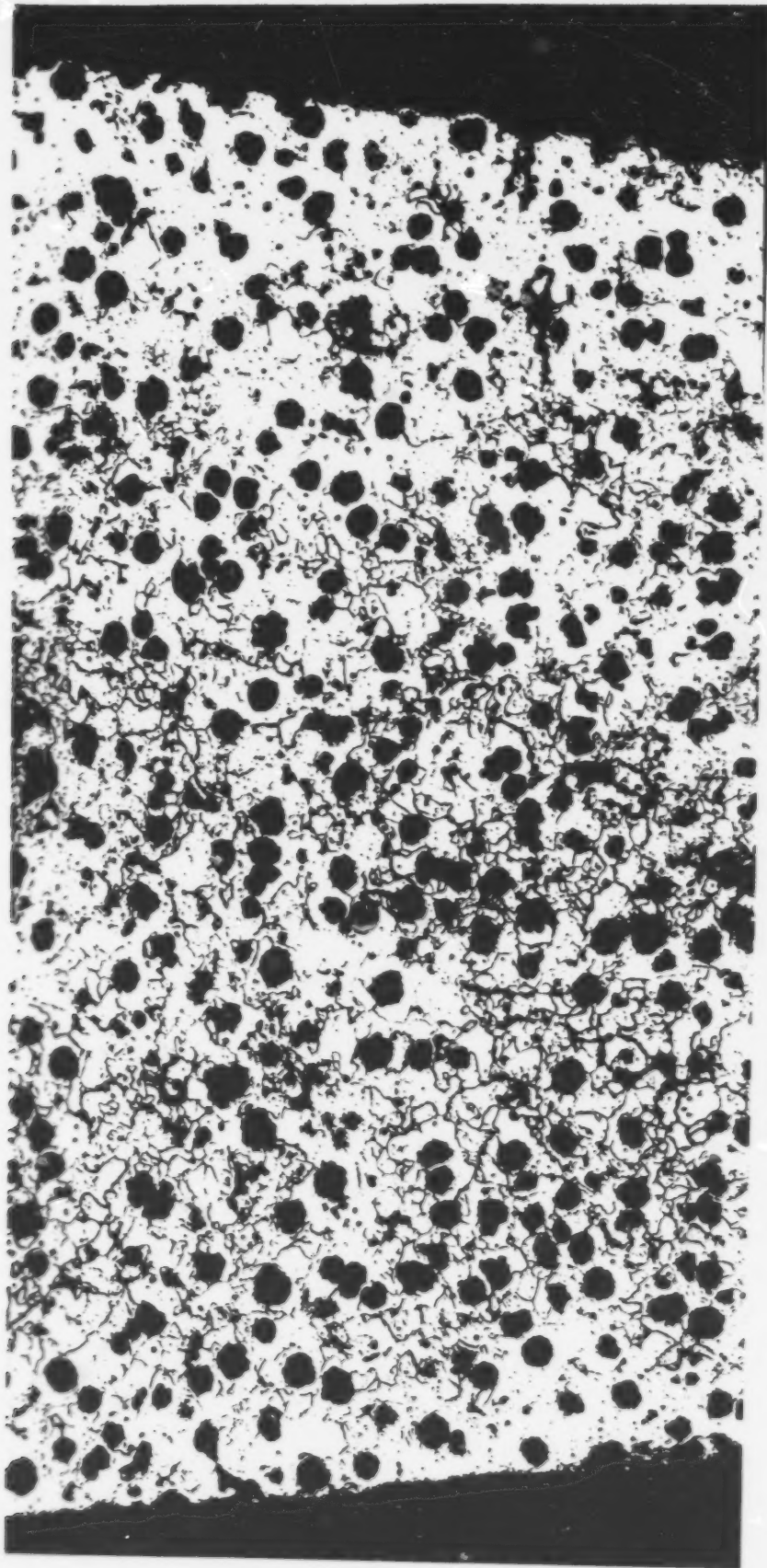
-62a-

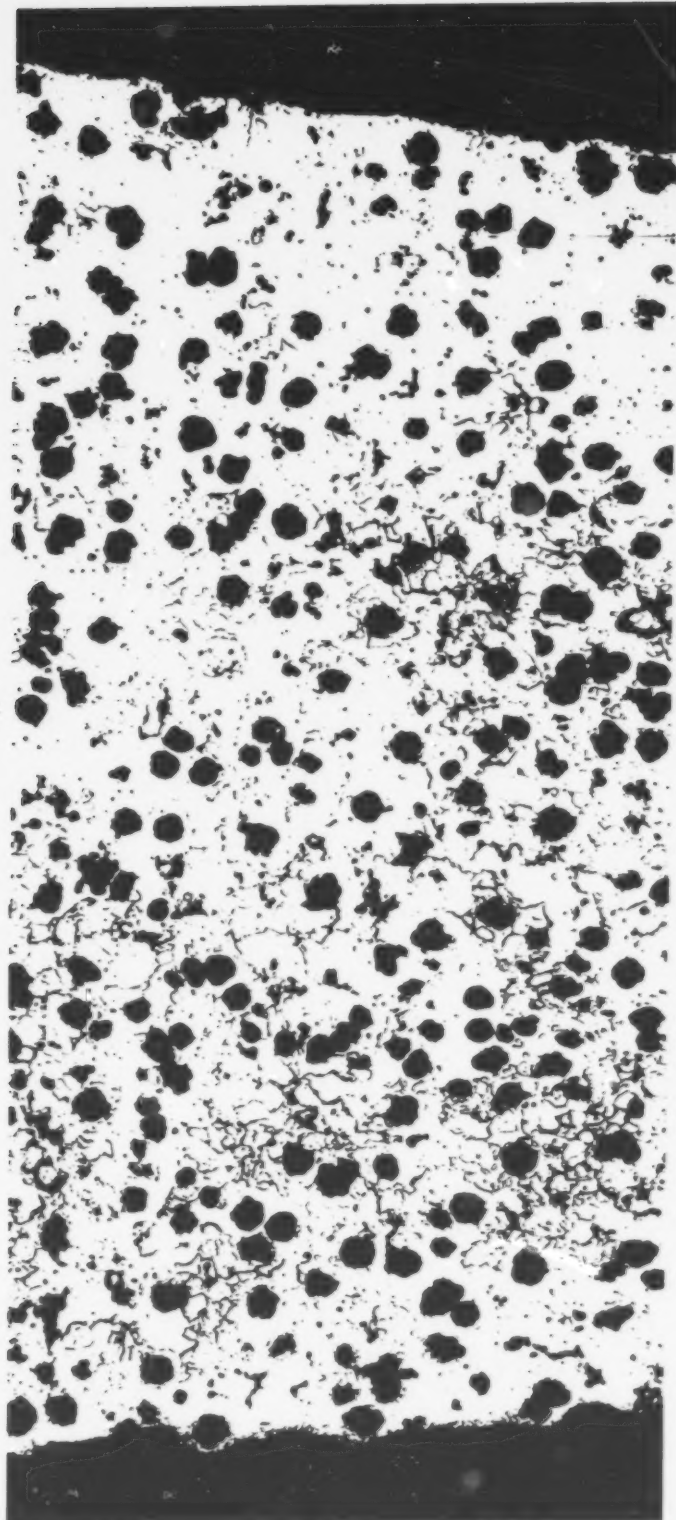


-62b-









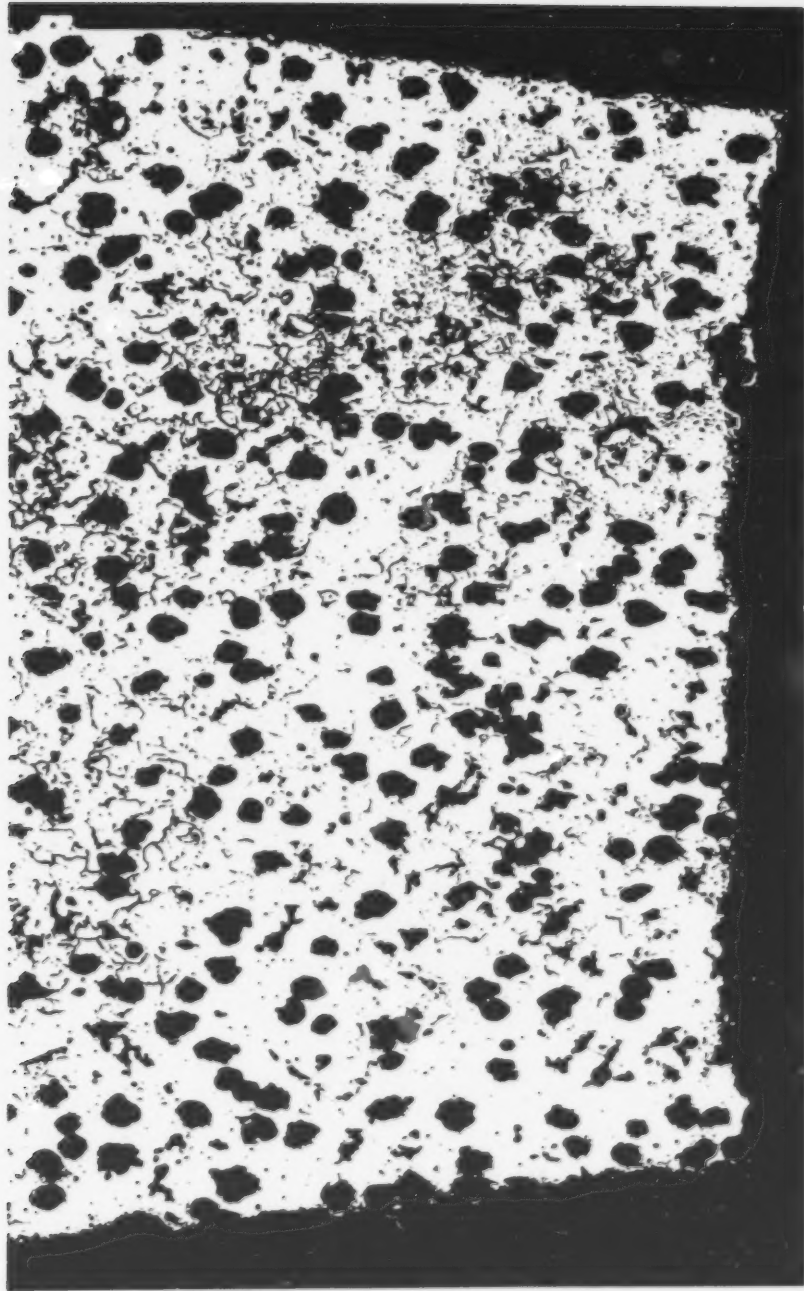


Fig. 44 Variation of Aspect Ratio of Modules with Distance from Node of Bend.

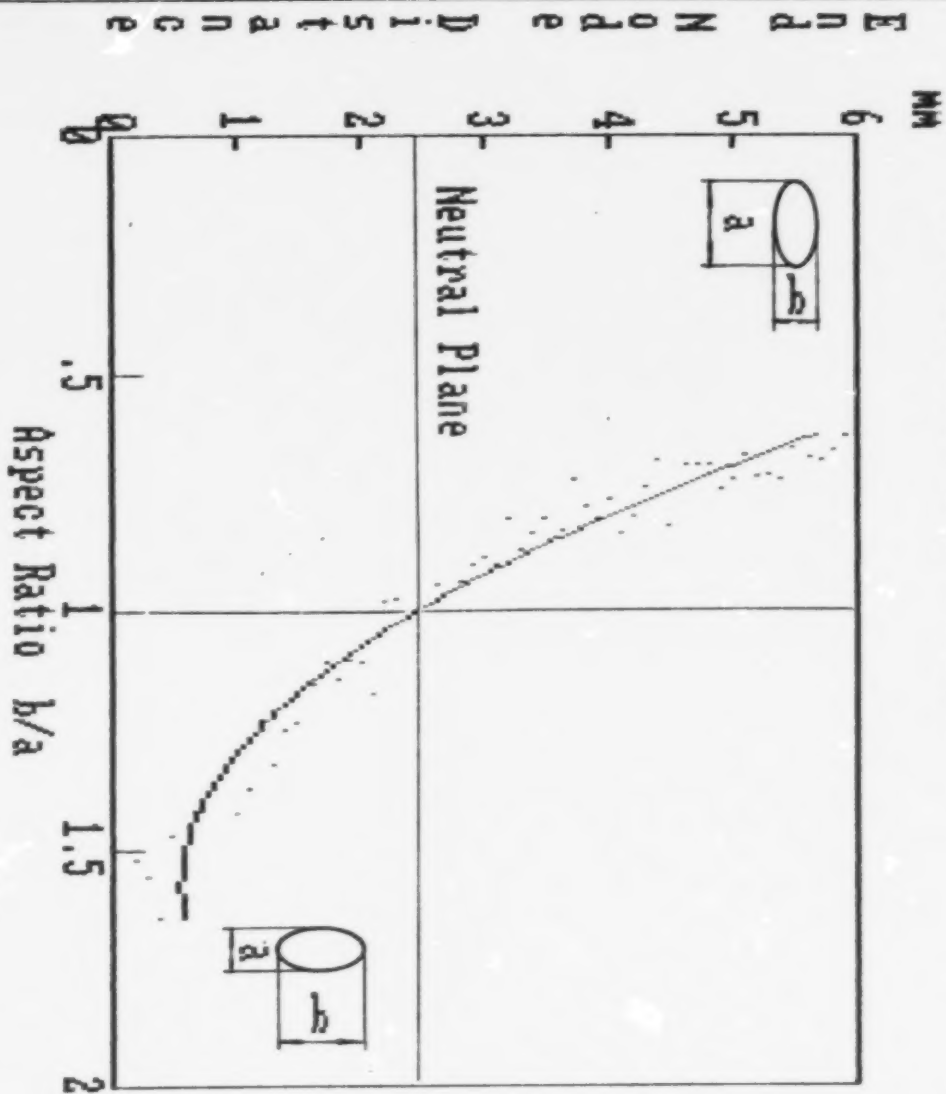


Fig. 45 Variation of Deformation with Distance from
Node of Bend.

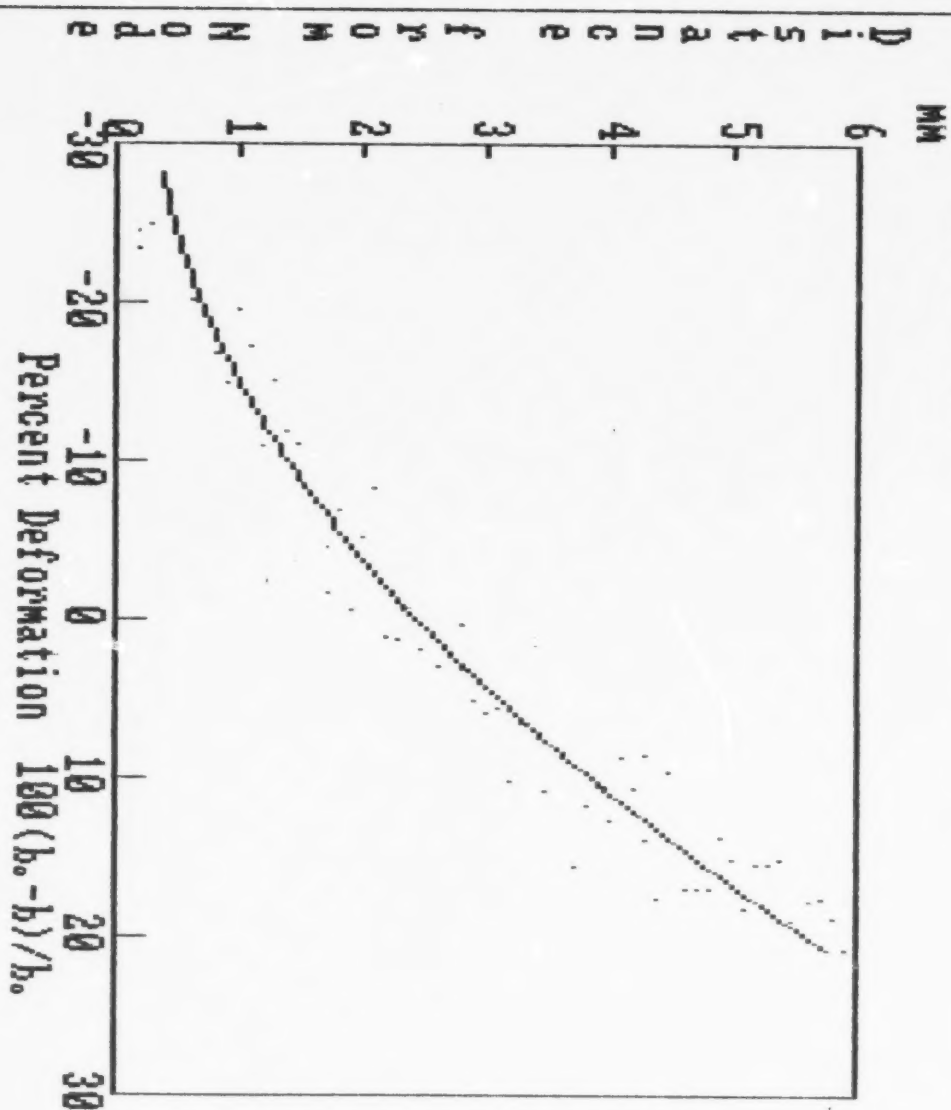


Fig. 46 Variation of Deformation with distance from node of bend.

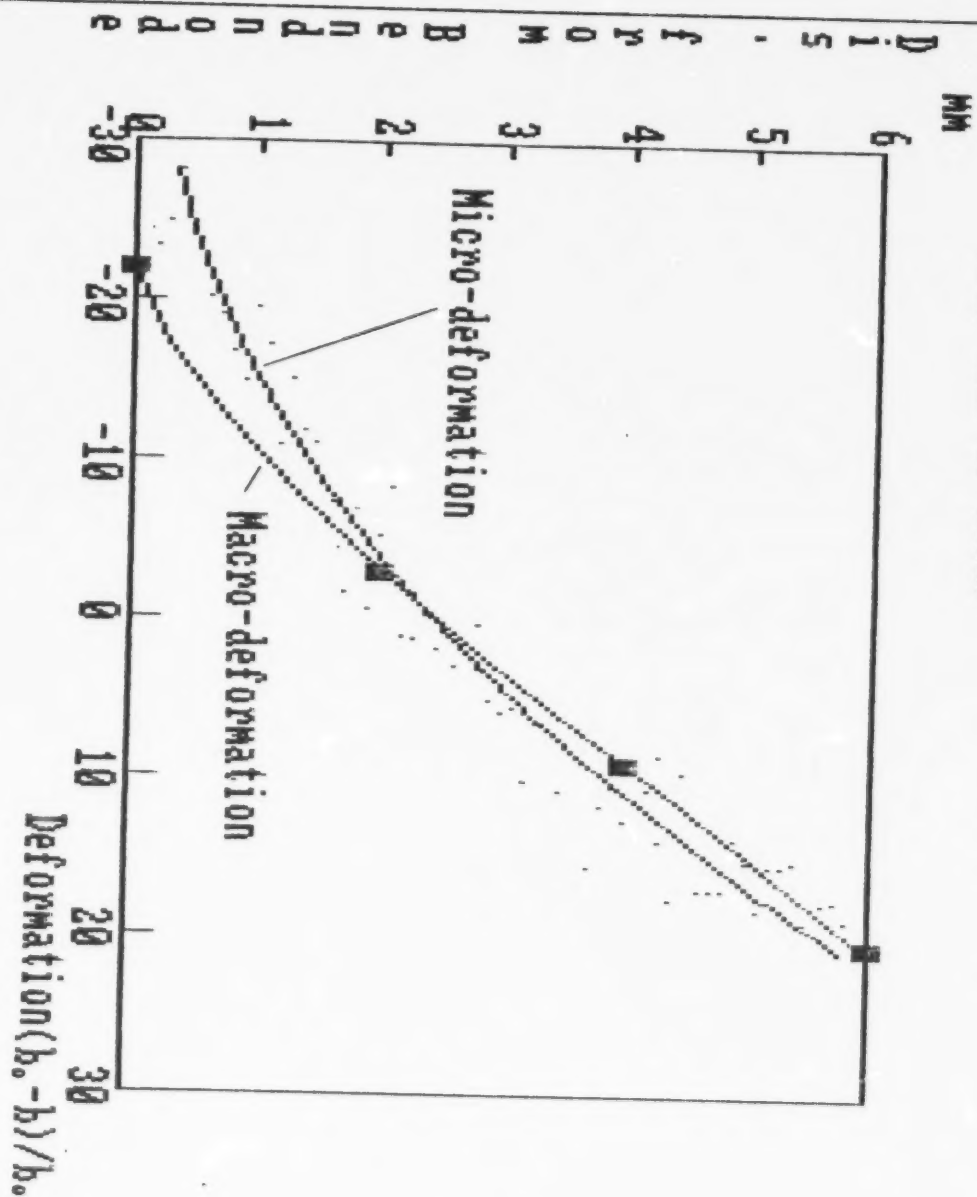




Fig. 47. Crack at the surface of the outer radius in bending test (100x).

TABLE 1

Alloy	C	Mn	P	S	Si	Cr	Ni
Valve Steel 1 J9415, Lister 22	0.51	8.16	0.038	0.002	0.21	21.38	3.54
Valve Steel 2 J9422 MS 158	0.55	7.54	0.035	0.003	0.15	20.43	1.73
Valve Steel 3 Lister 22	0.52	8.40	0.034	0.001	0.22	20.49	3.31
304A2 J 1006	0.53	1.52	0.032	0.002	0.39	18.32	8.12
Ferritic/pearlitic 3.6 nodular cast iron	----	----	-----	-----	2.4	-----	----
Austenitic nodular 3.3 cast iron	----	----	-----	-----	2.4	20.	----

FP DUCTILE IRON

=====

TABLE 2: COMPOSITION OF THE ALLOYS (%)

ALLOY	# 1	# 2	# 3	# 4
C	4.100	0.000	0.000	0.000
SI	1.400	99.500	0.000	0.000
FE	94.500	0.500	100.000	0.000
NI	0.000	0.000	0.000	85.000
MG	0.000	0.000	0.000	15.000
TOTAL	100.000	100.000	100.000	100.000

DESIRED COMPOSITION IN THE MELT (%)

C	SI	FE	NI	MG	TOTAL
3.600	2.400	93.330	0.570	0.100	100.000

QUANTITY TO BE MELTED (%)

ALLOY 1	ALLOY 2	ALLOY 3	ALLOY 4
87.805	1.177	10.349	0.667
(pig iron)	(Fe-Si)	(Fe)	(Ni-Mg)

AUSTENITIC DUCTILE IRON

=====

TABLE 3: COMPOSITION OF THE ALLOYS (%)

ALLOY	# 1	# 2	# 3	# 4	# 5
C	4.100	0.000	100.000	0.000	0.000
SI	1.400	99.500	0.000	0.000	0.000
FE	94.500	0.500	0.000	0.000	0.000
NI	0.000	0.000	0.000	85.000	100.000
MG	0.000	0.000	0.000	15.000	0.000
TOTAL	100.000	100.000	100.000	100.000	100.000

DESIRED COMPOSITION IN THE MELT (%)

C	SI	FE	NI	MG	TOTAL
3.300	2.400	74.200	20.000	0.100	100.000

QUANTITY TO BE MELTED (%)

ALLOY 1	ALLOY 2	ALLOY 3	ALLOY 4	ALLOY 5
78.512	1.307	0.081	0.667	19.433
(pig iron)	(Fe-Si)	(graphite)	(Ni-Mg)	(Ni)

TABLE 4

Cold Forgeability of Nodular Cast Irons

Materials	Ferritic	Ferritic/Pearlitic	Pearlitic	Austenitic
Reduction	60%	42%	35%	36%
	± 2	± 2	± 2	± 2

TABLE 5

Deformation Distribution in a Sectioned Specimen
After Compression

Area	Average b/a	Orientation of Nodules with Deformation Axis
Dead Zone	0.75	90°
Loop Area	0.34	90°
Center Area	0.21	90°
Shear Band	0.16	55°

TABLE 6

Local Strains around Crack Tips as Determined from
Changes in Aspect Ratio (b/a)

Area of Crack	Location of Tip in Sample	At Tip	Adjacent to Tip
Shear band	corner	0.12	0.36
	center	0.16	0.32
Hoop Area	center	0.86	0.33

TABLE 7

Specimen	Structure	Temperature (°C)	Reduction (%)	Comments
1	Annealed (ferritic)	900	70	No crack
2	Annealed (ferritic)	700	65	No crack
3	Annealed (ferritic)	700	66	No crack
4	Annealed (ferritic)	700	69	No crack
5	As cast (ferritic/pearlitic)	650	65	Crack
6	As cast (ferritic/pearlitic)	650	66	Crack
7	As cast (ferritic/pearlitic)	650	62	Crack
8	Austenitic	550	47	Crack



METALLURGICAL ENGINEERING DEPARTMENT

QUEEN'S UNIVERSITY

KINGSTON - ONTARIO - CANADA

4-9327

CONTRACT REPORT NO. OST84-00523

STUDY OF FORGEABILITY BASED ON LOCAL STRAIN
AND GRAIN STRUCTURE EFFECTS UNDER VARIED
DEFORMATION RATE AND TEMPERATURE

DSS Contract No. 20ST 23440-4-9327

Principal Investigator: Professor R.W. Smith

Metallurgical Engineering Department

Queen's University

Kingston, Canada

Report on Contract

Extension Work

MICROMEDIA

ABSTRACT

The Mechanical properties of the graphite spheroids in nodular cast iron (NCI) were evaluated by microhardness, deep etching, heat treatment and deformation tests of the NCI.

The results showed that the primary nodules formed during solidification did not change either in shape or mechanical properties during heating up to the solidus temperature. Thus heat treatment can only change the matrix. A layer of graphite usually deposits on the primary nodules during slow cooling after annealing. The nodular graphite was found to be brittle and incompressible during direct deformation of nodular cast iron. However, over a wide range of strains, the graphite spheroids deformed in the manner of the surrounding matrix.

The effects of nodule size and count on forgeability and mechanical properties were investigated by tensile testing. The results showed that the forgeability and tensile strength of NCI decreased with the decrease of nodular count and a subsequent increase in nodule size of NCI.

Correlation of forgeability of NCI with local strain measurement was made. For the same matrix of NCI very similar results were obtained from different methods of deformation, such as tensile, bending and radial ring-compression tests with similar stress conditions. The average aspect ratio of 0.66 $\sim$ 0.68 may be taken as a criterion of the maximum local strain of the annealed NCI for pure tension.

The feasibility of the fiducial grid technique for local strain measurement was also evaluated and shown to offer significant potential for detailed studies of local strain in future work.

Résumé

Les propriétés mécaniques des sphéroides de graphite dans la fonte nodulaire ont été évaluées par des tests de microdureté, de corrosion en profondeur, de traitement thermique et de déformation.

Les résultats montrent que les nodules primaires formés pendant la solidification ne changent ni de forme ni de propriétés mécaniques pendant le chauffage jusqu'à la température de fusion. Donc, le traitement thermique peut seulement modifier la matrice. Une couche de graphite se dépose habituellement sur les nodules primaires pendant le refroidissement lent après la recuite. Le graphite nodulaire s'est montré fragile et incompressible pendant la déformation directe de la fonte nodulaire. Cependant, les sphéroides de graphite se sont déformés de la même manière que la matrice environnante, dans une large gamme de déformation.

Les effets de la taille et du nombre de nodules sur la forgeabilité et les propriétés mécaniques ont été étudiés par des tests de tension. Les résultats ont montré que la forgeabilité et la résistance en tension de la fonte nodulaire diminuent avec le nombre de nodules et l'augmentation subséquente de la taille des nodules.

Une corrélation entre la forgeabilité de la fonte nodulaire et la mesure de la déformation locale a été établie. Pour la même matrice de fonte nodulaire, des résultats très similaires ont été obtenus pour différents modes de déformation: tests de tension, de flexion et de compression radiale dans des conditions de contrainte similaires. Un taux d'aspect moyen de 0.66 à 0.68 peut être considéré comme un critère de déformation locale maximale de la fonte nodulaire recuite, en tension pure.

La faisabilité de la technique de grille fine (microscope électronique) pour mesurer la déformation locale a aussi été évaluée et offre un potentiel significatif pour des études détaillées de déformation locale dans des travaux futurs.

1. MECHANICAL PROPERTIES OF NODULAR GRAPHITE

Nodular graphite is a typical second phase or inclusion in nodular cast iron (NCI). Since we have chosen NCI as the modelling material for our bulk forging study, we are interested in the deformation relationship between the graphite and the matrix in NCI, and the mechanical properties of both the graphite and matrices. The compositions of the ferritic-pearlitic (F-P) and austenitic NCIs prepared for this study are shown in Table 1. Much information about the mechanical properties of the matrices such as ferrite, pearlite and austenite is available and the tests of the mechanical properties of those matrices are not difficult to conduct. However, not much published information is available for the mechanical properties of the in-situ graphite in NCI, and it seems difficult to evaluate. In this study, microhardness measurements were made, deep-etching performed to better reveal the microstructure and heat-treatment was carried out to control the matrix.

1.1 Microhardness

Microhardness tests were conducted on a Leitz Wetzlar 60-366-002 microhardness tester. The specimens were fine-polished for the measurement. The microhardnesses of ferritic and pearlitic matrices were measured for annealed NCI; in addition, the microhardness of the austenitic matrix in NCI was measured in the as-cast condition using 100g weigh scale. The microhardness of in-situ nodular graphite was measured for as-cast ferritic-pearlitic (F-P) nodular cast iron specimens using the

lightest weigh scale of 15 g, since the nodular graphite is soft and brittle.

The results for the microhardness measurements of the different matrices are shown in Table 2; the average microhardness of in-situ nodular graphite was 38.8 ± 1.7 .

1.2 Deep-Etching

Deep-etching involves dissolving away much of the matrix and is a normal method of observing the graphite morphology of cast irons. Since it was difficult to measure the micro-hardness of nodular graphite before deformation and impossible after deformation, deep-etching was used to reveal the effect of deformation of the nodular graphite and the change of mechanical properties of nodular graphite after macro-deformation. The deep etching is schematically shown in Fig. 1. The fine polished specimen is put in a small beaker containing etchant of 10% HCl in alcohol. The small beaker is then put on the top of another beaker and surrounded by hot water in a large beaker. The water is kept at a temperature of 50-70°C. After etching for about 2 hours, the specimen is removed, rinsed thoroughly 2-3 times with alcohol, and then acetone, and finally dried.

Two specimens were deep-etched; one was a compressed ring and the other was a compressed cylinder. Both specimens were examined on a scanning electron microscope (SEM). It showed that only the nodules in the undeformed or very slightly deformed region could be seen (Fig. 2a). No deformed nodules were seen in the heavily deformed region because they became fragments after deformation and could not be held together, therefore leaving behind holes with the shape of the deformed nodules (Fig.

2b).

1.3 The effect of annealing on nodular graphite

In order to remove the effect of carbides on mechanical testing, NCI specimens are usually annealed before testing. This also influences the nodular graphite morphology.

Some as-cast NCI specimens with highly spherical nodules were annealed (as described in Final Report of DSS contract No. 20ST 23440-4-9327) by heating up to 900°C and then holding at that temperature for five hours. The specimens were furnace-cooled to 720°C, then forced to cool at a controlled rate of 5°C/hour for five hours, and finally cooled to room temperature by turning the power off to the furnace.

The microstructures of an NCI specimen before and after annealing are shown in Fig. 3. A layer of graphite was deposited on the surface of the primary graphite nodule, which did not change shape during annealing. The thickness of the deposited graphite depends on the amount of the carbon precipitated from the surrounding matrix. Since the carbon distribution in the matrix is not uniform, the graphite nodules will not be as spherical as primary graphite nodules. However, the properties of the nodular graphite will not change.

1.4 Nodular graphite at the deformed surface

Further useful information about the mechanical properties of the nodular graphite was obtained from the deformed surface of an NCI specimen. As shown in Fig. 4, the nodular graphite was "squeezed-out" from the free

surface or subsurface of a cylindrical ferritic NCI specimen after the specimen had been compressed by 47%. The nodular graphite behaves as an incompressible cheese-like region in the matrix. During compression the hydrostatic pressure builds up on a nodule of graphite until, if near a free surface, the matrix wall ruptures and the graphite is squeezed-out. The rupturing of the wall depends on the strength and thickness of the matrix. No squeezing out of graphite was seen on the surface of deformed pearlitic and austenitic NCI because of the higher strength of the matrix.

1.5 Results and Discussion

In-situ nodular graphite is formed during solidification by adding magnesium, and the nodular shape and size may be manipulated by controlling the cooling rate (1). The mechanism of nodular graphite formation has been described elsewhere and is not the subject of this work. It is of great interest that the nodular graphite is a compact phase i.e. incompressible. During plastic deformation, therefore, the volume of the NCI will not change. Thus an assumption of constant volume during plastic deformation can be made for the NCI. The microstructure of the as-cast nodular graphite was examined and no porous microstructure was found.

Nodular graphite in NCI containing 3.6% C remains stable up to the solidus temperature (eutectic temperature 1150°C) during heating. During annealing the carbon in the matrix will precipitate as the specimen cools down from the transition temperature 725°C, because the solubility of carbon decreases at lower temperatures. The precipitated carbon will be deposited on the surface of the original nodules. Likewise, the deposited layer of graphite can diffuse into matrix as the temperature increases.

The nodule shape after annealing will not be as spherical as that of the primary graphite nodules because of non-uniform deposition from various directions, but the enclosed primary graphite will not change in either shape or mechanical properties. Heat-treatment can only change the matrix, therefore the shape of any deformed nodular graphite will not change during heat treatment. Obviously, the anisotropy of the mechanical properties of NCI will develop after plastic deformation.

The microhardness of nodular graphite is very difficult to measure. Some problems arose during microhardness testing in this study. Firstly, most of the graphite nodules were so small that the indentations could not fit even with the smallest weigh scale of the tester. Secondly, the nodular graphite was found to be brittle and so it was difficult to get some indentations. Thirdly, since the graphite was not a good light-reflecting material, the indentation was hard to see. During the testing, some clearly visible indentations were obtained after many tries. The average hardness was $VHN\ 38.8 \pm 1.7$, but this reading is still in doubt because the indentations may have been on the broken graphite. The problems encountered during microhardness testing made all measurement very difficult.

Two cold-deformed specimens were deep-etched and then examined on a SEM. The results showed that only the nodules in the undeformed or very slightly deformed regions in the compressed specimens remained present after deep etching. Thus all the nodules in the more heavily deformed regions dropped out of their matrix cavities during metallographic preparation presumably because they had fractured during deformation, (Fig. 2b).

Further information about the deformation properties of nodular

graphite was obtained from the deformed surface of a ferritic NCI specimen after compression to 50%. Nodular graphite was squeezed out from the surface or subsurface during compression as noted earlier. This shows that the graphite can suffer some deformation and still remain coherent. Thus the nodular graphite behaved like an easily sheared incompressible medium which then exerted hydrostatic pressure on the surrounding walls. There may have been a compacting effect on the deformed nodular graphite, but there was no experimental evidence of this. It might affect the wear property of final forging products but appeared to have no significant effect on the mechanical properties of NCI.

1.6 Conclusions

1. In situ nodular graphite in NCI is brittle when tested for hardness. During extensive plastic deformation graphite nodules may fracture.
2. Heat treatment can only change the matrices of NCI but cannot change the primary graphite nodules. A layer of extra graphite will deposit on the primary graphite nodules during slow cooling following annealing. This can redissolve in the matrix if the NCI is heated up again. This layer can change the sphericity of nodules somewhat due to non-uniform deposition of the graphite during annealing. The deformed nodule shape cannot be changed by heat treatment and may result in the development of mechanical anisotropy of NCI by plastic deformation.

In choosing NCI as a modelling material it would appear that it can be treated as a material which after limited deformation contains cavities

filled with fragmented graphite nodules. This graphite is incompressible but is easily sheared.

2. THE EFFECTS OF NODULAR SIZE AND COUNT OF GRAPHITE PARTICLES ON THE FORGEABILITY OF NCI

As reported in Section 1, nodular graphite is a typical second phase inclusion in NCI. It behaves in a brittle manner and has less coherence with the matrix. NCI as a modelling material may be treated as a porous material which contains cavities filled with graphite conglomerates which behave as incompressible fluids. Therefore the shape, size, distribution and volume fraction of graphite nodules will have a strong influence on forgeability and mechanical properties of NCI. In this study, tensile testing was carried to for evaluate these effects.

2.1 Experimental

Three investment castings of NCI were made of the same composition (3.6%C, 2.4%Si, 0.57%Ni and 0.1%Mg) as that described earlier, each one containing five cast specimens of different diameter. The tensile specimens were machined from the annealed cast sections. The wax pattern and the microstructure of the castings are shown in Fig. 5 and 6. Since the castings were originally designed for compression testing, they are short. Hence, only small size specimens (4mm diameter and 16 mm gauge length) could be prepared and so the test was conducted on a Hounsfield tensometer. The specimens were tested in sets from the same casting in order to gather data for given conditions - i.e. same composition and heat treatment and so render comparison more easily accomplished.

2.2 Results and Discussion

The nodular shape, size and count can be controlled by the casting techniques as described in an earlier report. As shown in Fig. 5 and 6, as the diameter of a specimen increases, the nodular size increases and the nodular count decreases. This is associated with a reduction in the cooling rate and hence an increase in the time of solidification. Since the composition and heat-treatment were the same and the nodular shapes (sphericity) were similar for the five specimens of each set (or even for all the specimens of three sets) then the effects of nodular size and count on forgeability and mechanical properties could be evaluated by comparing mechanical data obtained from the tensile test.

The results of the tensile test are shown in Tables 3 and 4. It was assumed that the volume fraction of nodular graphite remains relatively constant during these studies. Table 3 shows that the forgeability of NCI decreases with the decrease of nodular count and a subsequent increase in nodular size and also shows that the forgeability of NCI decreases with the increase of the diameter or thickness of the castings. This is similar to the effects of casting thickness and nodular count on the mechanical properties reported by some researchers (2,3) and would be expected since both are inversely correlated. In this study, the ultimate tensile strength was also measured and the results are shown in Table 4. This indicates that the tensile strength decreases with increasing casting thickness, i.e. decreasing the nodular count and increasing the nodule size (specimen 3 behaves anomalously for reasons as yet unknown).

However the results of the tensile test do show the effect of

nodular count and size on the forgeability and the mechanical properties. For information on the influence of volume fraction of nodular graphite, matrices and graphite shape, etc., more detailed experiments will have to be done in a future study.

3. CORRELATION OF FORGEABILITY OF NCI WITH STRAIN MEASUREMENT

In order to get more information about local strain at or near crack tips, a radial ring-compression test was conducted.

3.1 Ring Testing

Ring specimens of annealed NCI with dimensions of 22.25mm outer diameter, 12.9mm inner diameter and 6.25mm width were compressed radially on a Instron machine. A cross-head speed of 0.01 in/min and a chart speed of 2 in/min was used. The crack initiation was determined by the load drop in a time-load recording during compression. The rings could be compressed radially from initial outer diameters of 22.25mm to 18.85mm. The crack initiated at the inner surface of the bottom part of the ring, as shown in Fig. 7. The local strains at or near the crack tip (Fig. 8) were determined by measuring the aspect ratio b/a of the deformed nodules on a microscope. 57 nodules were measured, giving an average aspect ratio b/a of 0.66. The corresponding micro-deformation in terms of reduction or elongation was 24%.

3.2 Results and Discussion

The local strain in terms of aspect ratio of the deformed nodules at the crack tip for radial ring-compression of the annealed NCI was 0.66 and

the corresponding microdeformation in terms of elongation of nodules was 24%. This is in good agreement with the results obtained from tensile and bending tests for the same material, i.e. the aspect ratio of the deformed nodules in the tensile test before breaking was 0.68 (corresponding to 23% average elongation of the nodules), while the aspect ratio of deformed nodules at the crack tip of the bending specimen was 0.66 (corresponding to 24% average elongation of the nodules).

For the same matrix of NCI, very similar results could be obtained from different deformations such as tensile, bending and radial ring-compression tests with similar stress conditions, i.e. under tensile stress. It is clear that the average aspect ratio of 0.66 & 0.68 may be taken as a criterion of the maximum local strain of the annealed NCI for pure tension.

4. FEASIBILITY STUDY ON THE FIDUCIAL GRID TECHNIQUE FOR LOCAL STRAIN MEASUREMENT

The fiducial grid technique employs a method mainly used in the electronics industry for manufacturing integrated circuits (4). Some investigators have used this technique for the observations on the surface of the deformation mechanisms of metals, such as grain-boundary sliding, slip formation and strain path (5). This technique seems very useful for the study of forgeability based on local strain measurement.

The main advantages and disadvantages of the fiducial grid technique for the purpose of local strain measurement in the study of forgeability

may be summarised as follows:

The advantages are:

- a. High resolution
- b. High regularity and accuracy
- c. No sensitivity to premature failure, as experienced in photoetched or scribed grids (6).

The main disadvantages of this technique are:

- a. Relatively time consuming to perform
- b. A detailed procedure for the production of the grids, including specimen polishing, uniform coating, electron beam exposure, developing, noble metal evaporating and stripping of the resist polymer must be established.
- c. The technique tends to be limited to a small selected area (7)
- d. The simplest specimen shape appears to be that of a flat tensile specimen.

Our research program to evaluate the potential of the fiducial grid technique has been successfully completed.

Consideration is now being given to the preparation of fiducial grids on plane sections and welding these sections together by a "hipping" (Hot Isostatic Pressing) to form an integral sample for compression testing. The grids on each section would be uniformly oriented on a common axis and the examination of longitudinal sections would be made after compression and sectioning. Some of the problems that have to be taken into account when using this method are:

- a. The diffusion of the grid lines into the matrix during "hipping". The temperatures of "hipping" of specimens are 60 to 90 percent of the solidus temperature of the specimen material, thus the melting

point of grid material must be as high as possible to reduce diffusion effects.

- b. The oxidation of the specimen surface can cause problems in "hipping". Thus it is necessary to first coat an ion-cleaned surface with a noble metal by sputtering before putting the grid down. Then subsequent hipping will weld the two faces together.
- c. The analysis of the local strain of the deformed specimen requires the specimen section to display the grids in a longitudinal section. This requires carefully controlled sectioning but may be achieved with electro-discharge-machining, followed by fine polishing.

It is considered that the development of the fiducial grid technique is essential to providing accurate local strain measurement to further collaborate the nodule deformation technique described earlier.

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Table 1: COMPOSITION OF F-P NODULAR CAST IRON AND ITS CHARGE ALLOYS

COMPOSITION OF THE ALLOYS (%)

ALLOY	#1	#2	#3	#4
C	4.100	-----	-----	-----
SI	1.400	99.500	-----	-----
FE	94.500	0.500	100.000	-----
NI	-----	-----	-----	85.000
MG	-----	-----	-----	15.000
TOTAL	100.000	100.000	100.000	100.000

C	SI	FE	NI	MG	TOTAL
3.600	2.400	93.330	0.570	0.100	100.000

QUANTITY TO BE MELTED (%)

ALLOY 1	ALLOY 2	ALLOY 3	ALLOY 4
87.805	1.177	10.349	0.667
(pig iron)	(Fe-Si)	(Fe)	(Ni-Mg)

Table 2. THE MICROHARDNESS OF THE MATRICES OF NCI

Matrix	Hardness (VHN)
Ferrite	235.1 ± 4%
Pearlite	200.3 ± 2.7%
Austenite	349.5 ± 3%

TABLE 3: THE FORGEABILITY OF ANNEALED NCI ELONGATION (%)

Specimen	1	2	3	4	5
Diameter (mm)	15	20	25	30	35
Set 1	9	6	8	6	4
Set 2	10	12	8	7	4
Set 3	8	7	7	4	5
Average	9	8.3	7.7	5.7	4.3

TABLE 4: THE TENSILE STRENGTH OF ANNEALED NCI (psi)

Specimen	1	2	3	4	5
Diameter (mm)	15	20	25	30	35
Set 1	46,000	42,000	54,400	26,100	27,200
Set 2	49,900	52,200	53,300	28,400	24,900
Set 3	47,600	44,200	55,600	27,200	24,900
Average	47,800	46,100	54,400	27,200	25,700

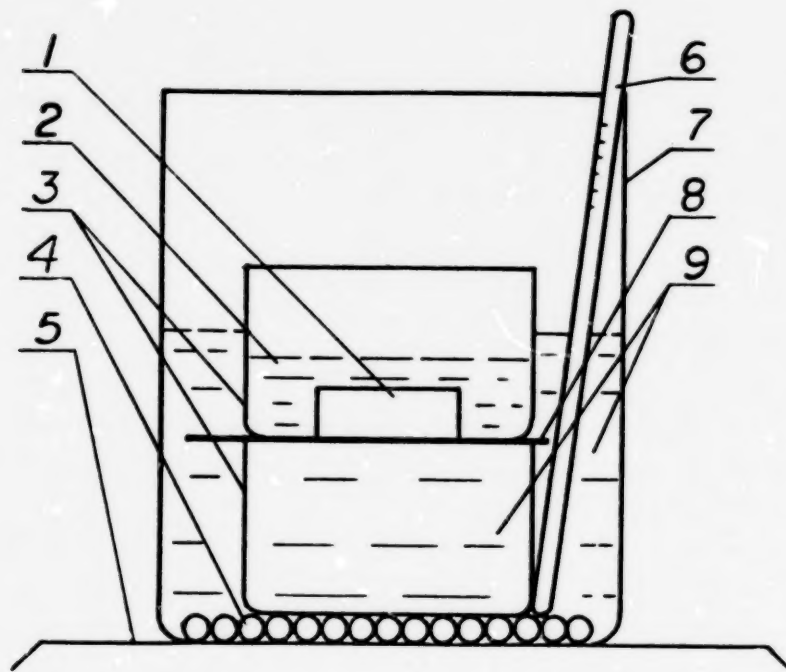


Fig. 1. A schematic illustration of deep etching

1) Specimen	6) Thermometer
2) Etchant	7) Large beaker
3) Small beakers	8) Wire mesh
4) Beads	9) Hot water
5) Hot-plate	

(a)



(b)



Fig. 2: (a) The morphology of the undeformed nodules in the dead zone of a compressed specimen by deep etching.
(b) The "empty" nodule pockets in heavily deformed areas, as shown after deep etching.

(a)



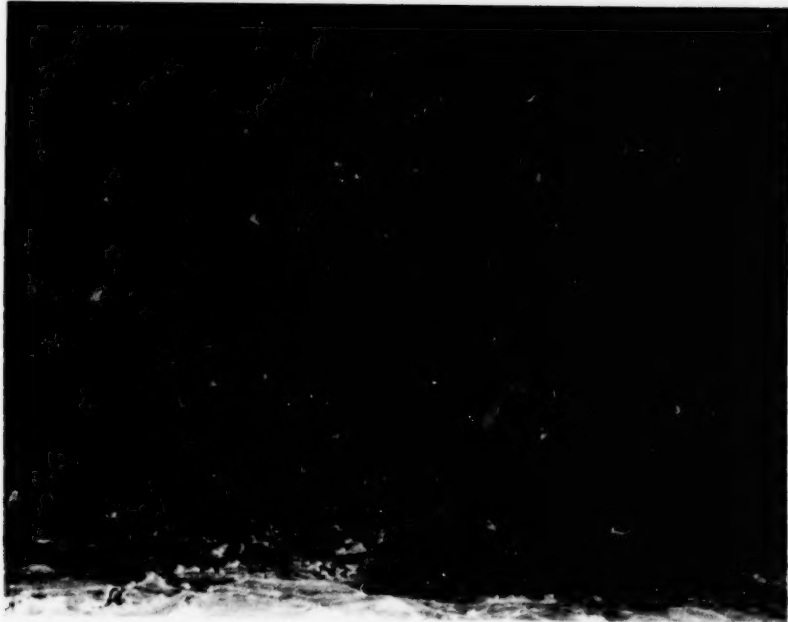
(b)



Fig. 3: Microstructures of the graphite nodules

- a) before annealing
- b) after annealing showing a layer of graphite deposited on the primary graphite nodules. Unetched (300X).

(a)



(b)

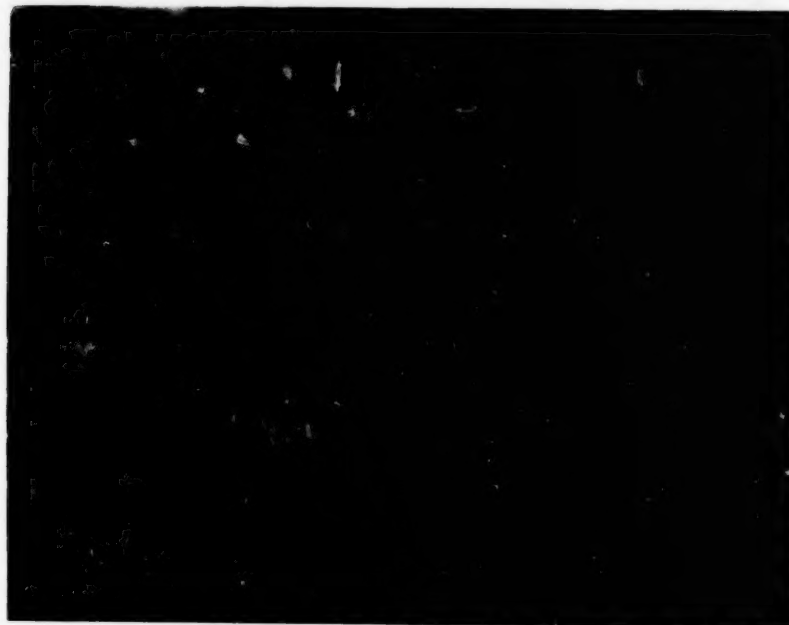


Fig. 4: (a) (b) Nodular graphite was squeezed out from the free surface of a cylindrical specimen during compression.

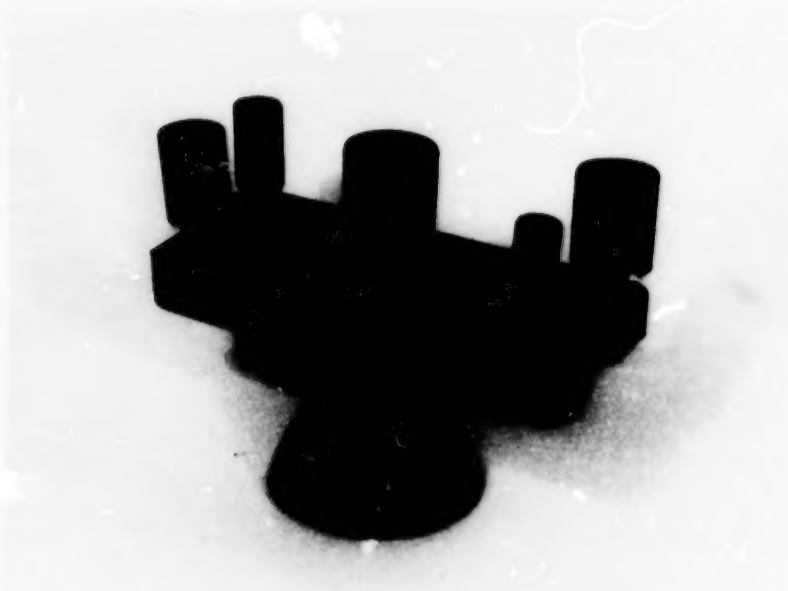


Fig. 5: Wax pattern of ceramic mold for nodular cast iron.

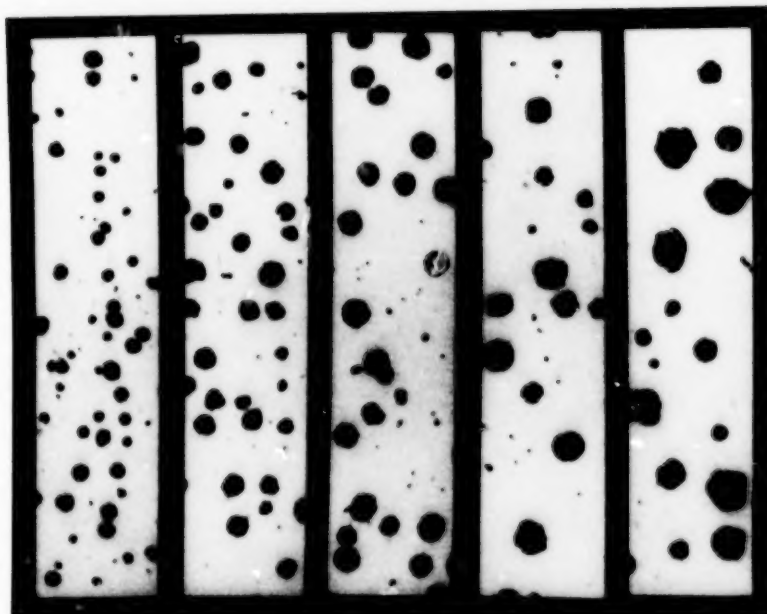


Fig. 6. Different nodule sizes and numbers from specimens shown in Fig. 5, unetched (100x).

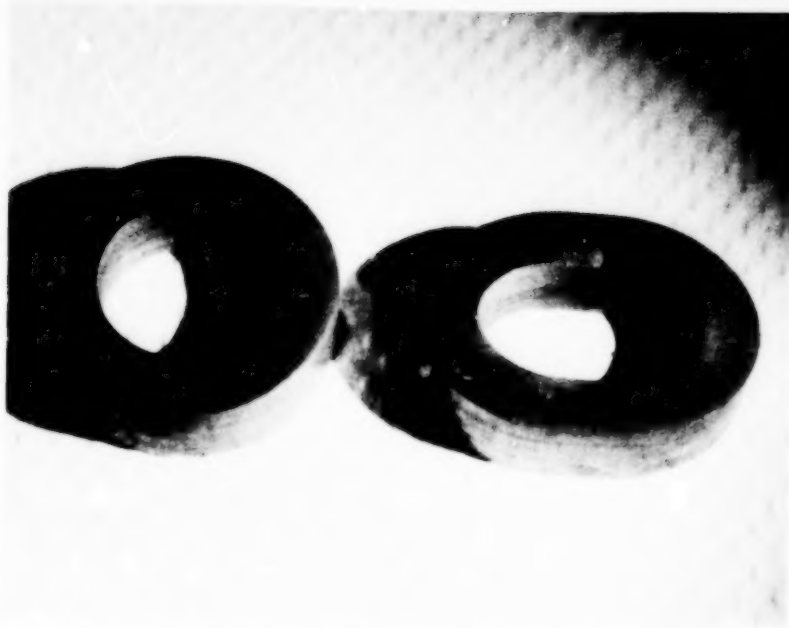


Fig. 7: Ring specimen before and after deformation.



Fig. 8: Crack tip of the ring specimen after radial compression.
Unetched (60X).